DETERMINATION OF RADIOLOGICAL HAZARD LEVELS IN SOIL, MINE TAILINGS AND ROCK SAMPLES FROM SELECTED GOLD MINES IN BUSIA DISTRICT, UGANDA

BY

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DECLARATION

I, Eling Jimmy do hereby declare that this is my original work. It has not been partially or in whole submitted to any academic Institution for an academic award.

Signed:...

Date:............15/11/2018...........

DEDICATION

This work is dedicated to my dear wife, Mrs Scovia Eling for the moral support she accorded to me right from the beginning up to the end of the study.

ACKNOWLEDGEMENT

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ABSTRACT

This study was designed to determine radiological hazard levels in soil, mine tailings and rock samples from Agata, Okame, Busia 90 and Greenstone Resource Limited Gold mines in Busia District. The specific activity of the radionuclides were determined using NaI (Ti) scintillation detector and the values were then used to determine the radiological hazard parameters due to radionuclides in the samples from the mines under study.

The specific activity of ^{238}U in soil, mine tailings and the rock samples from the four gold mines ranged from 18.7 Bqkg^{-1} to 27.9 Bqkg^{-1}, 7.4 Bqkg^{-1} to 13.2 Bqkg^{-1} and 1.7 Bqkg^{-1} to 27.8 Bqkg^{-1} respectively. The specific activity of ^{232}Th in soil, mine tailings and rock samples from the mines ranged from 60.8 Bqkg^{-1} to 98.8 Bqkg^{-1}, 25.1 Bqkg^{-1} to 32.7 Bqkg^{-1} and 2.3 Bqkg^{-1} to 66.6 Bqkg^{-1} respectively while that of ^{40}K in soil, mine tailings and rock samples ranged from 53.6 Bqkg^{-1} to 211.8 Bqkg^{-1}, 5.7 Bqkg^{-1} to 217.3 Bqkg^{-1} and 2.1 Bqkg^{-1} to 120.1 Bqkg^{-1} respectively. The Specific activity values of ^{232}Th in soil sample from each of the four gold mines were above the worldwide average value of 30 Bqkg^{-1}. It is only Greenstone mine tailings and Okame rocks that had higher activity for ^{232}Th than the world wide average value. The Absorbed Dose rates in soil, rock and mine tailings samples ranged from 41.7 nGyh^{-1} to 76.3 nGyh^{-1}, 13.3 nGyh^{-1} to 32.7 nGyh^{-1} and 2.3 nGyh^{-1} to 58.0 nGyh^{-1} respectively. Only Okame had a higher value for soil than the world wide average value of 60 nGyh^{-1}. The Annual Effective Dose rates in soil, mine tailings and rock samples ranged from 0.051 mSvy^{-1} to 0.093 mSvy^{-1}, 0.024 mSvy^{-1} to 0.050 mSvy^{-1} and 0.011 mSvy^{-1} to 0.047 mSvy^{-1} respectively which were lower than the ICRP recommended value of 20 mSvy^{-1}. The internal hazard indices in soil, mine tailings and rock samples ranged from 0.30 to 0.56, 0.15 to 0.27 and 0.02 to 0.43 respectively. External hazard indices of the radionuclides in the soil, mine tailings and rock samples ranged from 0.27 to 0.47, 0.10 to 0.23 and 0.01 to 0.36 respectively. They were found to be below unity as per ICRP, 2007 maximum permissible limit. The Excess Lifetime Cancer Risk (ELCR) ranged from 6.90×10^{-5} to 1.93×10^{-4} was lower than the ICRP maximum permissible excess lifetime cancer risk limit of 5.60×10^{-2}. Despite the low radiological health risk, miners need protective gears particularly at Okame and Greenstone mines and further research need to be done to validate these findings.

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Human beings are continually being exposed to ionizing radiation from both artificial and natural sources (Taskin et al. 2009). The natural sources of ionizing radiation include radiation arising from cosmic rays and those from terrestrial sources in the earth's soils and rocks (UNSCEAR, 2000). The natural sources of radiation effectively cover all living and non-living things on the surface of the earth and the radiation from these sources constantly irradiate the general public. The general public are therefore continually exposed to this abundant natural sources of ionizing radiation as opposed to artificial sources which when it occurs may come in a large dose. The common radiations from these sources that can impact on materials they irradiate include gamma rays, beta particles, alpha particles and neutrons. They are all results of disintegration of unstable radionuclides. Gamma rays of all common ionizing radiations are the most energetic and penetrating. They are known to be emitted by naturally occurring radionuclides such as ^{40}K, ^{238}U and ^{232}Th from rocks, soils and others (Taskin et al. 2009). These gamma emitting radionuclides and their decay products exist at trace levels in most soils and rocks; their concentrations vary from place to place depending on the geology and geographical conditions of the place (Xinwei et al. 2006).

According to Mason & Moore, 1982, higher radioactivity levels are associated with igneous rocks such as granite rocks which contain minerals titanite, monazite, zircon, and apatite among others which have these radionuclides in significant quantities (Uosif, M.A.M. 2007). Uranium and thorium are found mainly in accessory minerals such as and shale which are constituents of granitic rocks and lower levels with sedimentary rocks.

According to UNSCEAR, 2000, human activities such as mining and processing of minerals have been identified as one of the potential sources of exposure to naturally occurring radioactive materials which could have been buried deep in the ground. Gold is found in free form and in compound form. It is usually associated with earth's minerals such as quartz, lead, copper, zinc and calcite among others which are contained in some rock types having enhanced amount of terrestrial radionuclides.

In Uganda, gold is widely distributed and mined in a few areas but not limited to Busia, Mubende, Kigezi, Buhweju and Karamoja. A study done by Turyahabwa,S. E . R. (2016), on mine tailings from Mashonga gold mine South-western Uganda has revealed high mean absorbed dose of 181.2 ± 66.8 nGyh^{-1} above the world wide average of 60 nGyh^{-1}. This therefore requires that safety measures be taken to minimise the risk of miners or nearby people being exposed to high radiation dose.

The rock types in Busia district according to Mbonipa, A. (2005) are mainly mafic rocks, granites and banded quartzite. The presence of granite rocks is associated with high radioactivity and if these granite rocks are spread all over the mines then, the radiation levels at the mines may be high.

In Busia district gold is recovered from quartz reef and alluvial deposits using rudimentary method of mining and processing gold from the ore. The miners do not put on protective gears such as nose mask which could protect them from inhaling radionuclides particles in the dust generated during mining and processing stages. According to NAS, (1988), inhalation of the most radiotoxic gas radon (^{222}Rn) from the dust is associated with increased risk of lung cancer. The practice observed of the miners in the gold mines in Busia district puts miners and people who live near the mines at a risk of suffering from radiological related illnesses if the mines have high radiation levels above the recommended safe limits set by ICRP, 1999.

1.2 Statement of the Problem

In Busia district, there is limited data on radiological studies done on the gold mines to determine radiological health risk to the miners and the public who are linked to the mines. This information is needed to guide people linked with the mines so that they are protected as per ICRP, 1999 guidelines.

1.3 Purpose of the Study

Due to the problem cited above, this study therefore was designed to determine radiological hazard levels in soil, mine tailings and rock samples from the four selected Gold mines in Busia and compare them with the ICRP standards.

1.4 Objectives of the Study

The objectives of this study were to determine:

(i)   Specific activity of gamma ray emitting radionuclides in soils, mine tailings and rocks samples from the selected mines.

(ii)   Absorbed dose rate in the soil, mine tailings and rock samples.

(iii)   Annual effective dose equivalent in the soil, mine tailings and rock samples.

(iv)   Hazard indices in soil, mine tailings and rock samples from the selected gold mines.

(v)   Excess lifetime cancer risk to the miners due to the gamma ray emitting radionuclides in the soil, mine tailings and rock samples from the selected mines.

1.5 Scope of the Study

The study was restricted to four mines that is Agata and Okame gold mines in Amomikakinei parish with GPS coordinates N 0° 34' 0.0001″ E 34° 4' 59.998″ and N 0° 24' 16.103″ E 34° 1' 10.497″ respectively; Busia 90 and Greenstone Resource Limited gold mines in Tira parish with GPS coordinates N 0° 27' 38.769″ E 34° 6' 41.263″ and N 0° 26' 4.742″ E 34° 14' 31.774″. These mines were selected on the basis of large number of people involved in mining activity and concentration of gold mines in the areas as shown in the geological map of Busia in Figure 1.1 below.

Source: Hester & Boberg, 1996
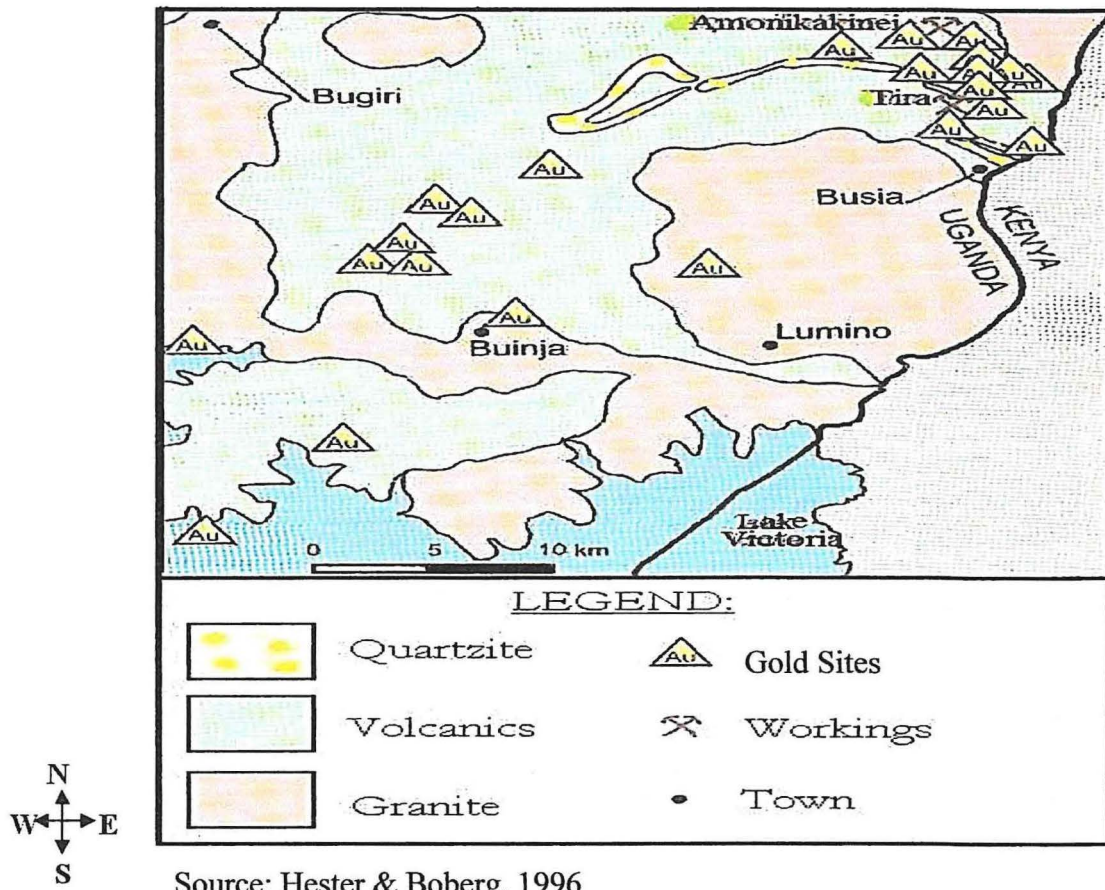
Figure 1. 1: Geological map of Busia showing gold Sites

A total of 32 soil, 20 rock and 10 mine tailings composite samples were taken from Agata, Okame, Busia 90 and Greenstone Resource Limited gold mines. The number of soil, mine tailings and rocks samples differ from each other owing to their availability at the sample sites. The samples were taken to the laboratory for preparation and analysis.

The results of this study were focused on specific activity and the following radiological hazard parameters: absorbed dose rate, annual effective dose equivalent, hazard indices and excess lifetime cancer risk. Gamma ray spectrometry system coupled with Nal (TI) scintillation detector was used to measure count rates that were used to determine specific activity concentrations of gamma ray emitting radionuclides as the basis to determine radiological hazard levels.

1.6 Significance of the Study

This study focused on Agata and Okame gold mines in Amonikakinei parish; Busia 90 and Greenstone resource limited gold mines in Tira parish all in Busia District. The values of specific activities, absorbed doses, hazard indices and annual effective dose equivalent in this study can provide useful information to Uganda Atomic Energy Council (UAEC) for considering safe practices for miners to observe and other people operating in the neighborhood of the mines. The Ministry of Health (MoH) may find the values of Excess Lifetime Cancer Risk useful in diagnosis of cancer cases of people coming from the regions under study.

The results of specific activity of gamma emitting radionuclides, Hazard Indices, Absorbed Dose Rate, Annual Effective Dose Equivalent and Excess Lifetime Cancer Risk values obtained in this study could be used as a base line data by future researchers.

CHAPTER TWO: REVIEW OF RELATED LITERATURE

2.1 Introduction

This chapter describes the sources of primordial radionuclides in the environment and the chain involved in ^{238}U and ^{232}Th decay series. It also describes the ^{40}K decay process. The biological effects of ionizing radiation to human beings as a result of inhalation and ingestion of the radiation through different pathways has been discussed. Also, environmental radiation studies done in different countries with their corresponding results were reviewed from the available literature that were sourced from internet, text books and academic journals to confer a better understanding of the concept of human exposure to the radionuclides.

2.2 Natural Radioactive Series

The naturally occurring radionuclides include primordial radionuclides such as ^{238}U, ^{232}Th and ^{40}K (UNSCEAR, 2000).

The radionuclides in the uranium decay series cannot be assumed to be in radioactive equilibrium, so they decay to produce the most stable isotopes ^{206}Pb in the decay series as shown in the Figure 2.1 below.
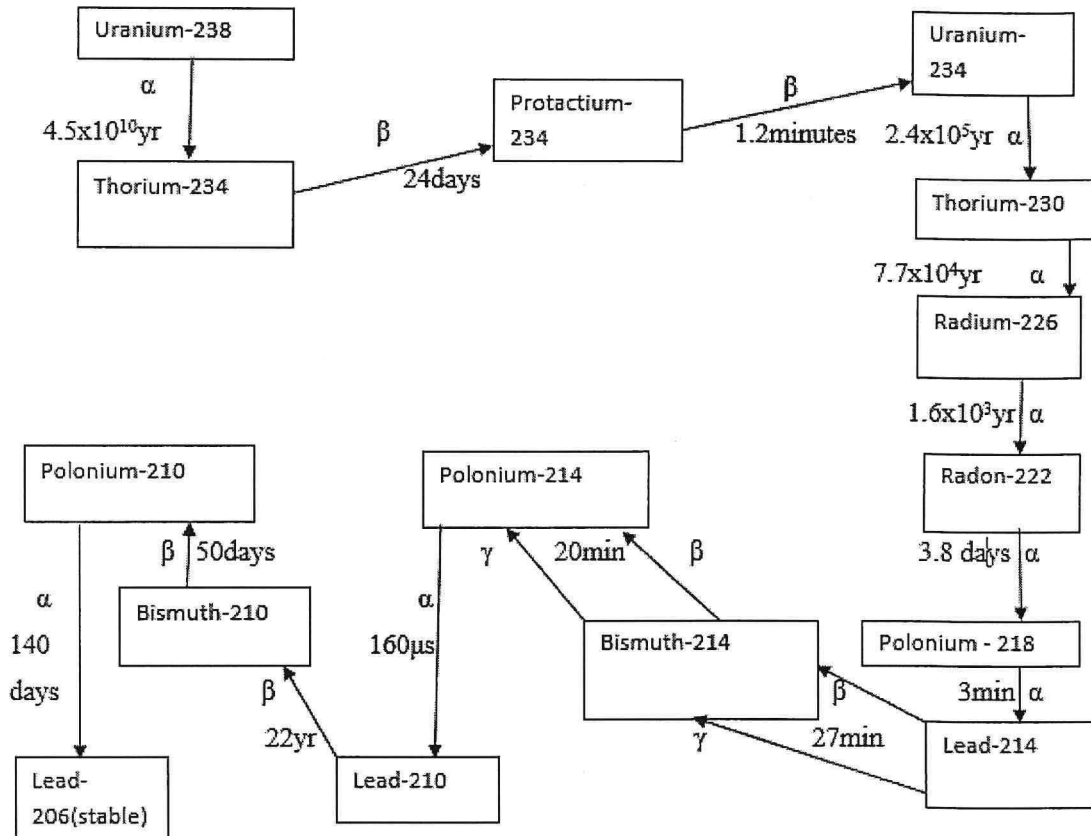
Source: Attallah et al. (2012)

Figure 2. 1: Radioactive Decay chain of Uranium -238

The isotopes ^{238}U and ^{234}U are in approximate equilibrium, as they are separated by two much short-lived nuclides, ^{234}Th and ^{234}Pa. The decay process itself may, however, allow some dissociation of the decay radionuclide from the source material, facilitating subsequent environmental transfer. Thus ^{234}U may be somewhat deficient relative to ^{238}U in soils and enhanced in rivers and the sea. The radionuclide ^{226}Ra in this chain may have slightly different concentrations than ^{238}U, because separation may occur between parent ^{230}Th and uranium and because radium has greater mobility in the environment. ^{226}Ra is considered as the most radiotoxic natural radionuclide in ^{238}U decay series. The ^{226}Ra decays to Radon which consists of three isotopes; ^{219}Rn, ^{220}Rn and ^{222}Rn. Radon normally emanates from materials carrying Uranium (soil, sand, rocks, gravels etc).

Despite the short half-life of ^{222}Rn (3.84 days), it presents a long term hazard, since the decay of ^{226}Ra (half-life of 1,600 years) constantly produces new radon. In addition, the tailings also contain the predecessor of ^{226}Ra in the decay chain including ^{230}Th, which decays with half-life of 75,400 years, again constantly producing ^{226}Ra. When ^{222}Rn gas is inhaled it gets to the lungs and deposits large amounts of energy to the surrounding tissue which may bring severe biological damage that might cause lung cancer (NAS, 1988). The decay products of ^{226}Ra include the gaseous element radon, which diffuses out of the soil, reducing the exposure rate from the ^{238}U series. The radon radionuclide in this series, ^{222}Rn, has a half-life of only a few days, but it has two longer-lived decay products, ^{210}Pb and ^{210}Po, which are important in dose evaluations. The final decay stable product in this series is ^{206}Pb. Similarly, the radionuclides in ^{232}Th decay series cannot be assumed to be in radioactive equilibrium, they decay to form ^{208}Pb as the most stable isotopes of this decay series as shown in the Figure 2.2.
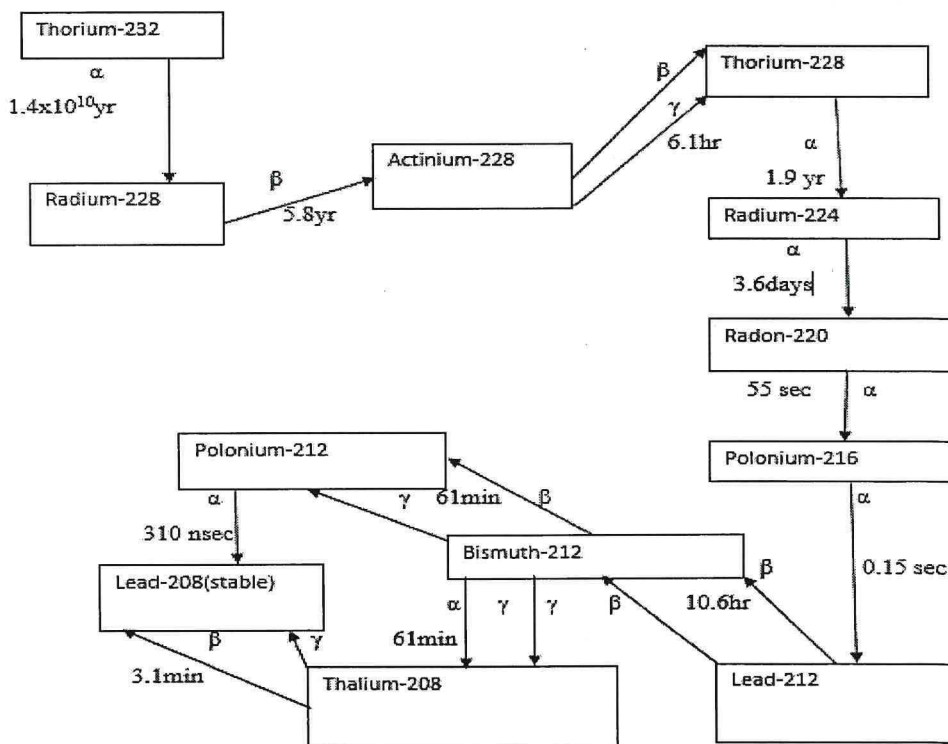
Source: Attallah et al. (2012)

Figure 2. 2: Radioactive Decay chain of Thorium-232

In nature almost all thorium is ^{232}Th with half-life of 14 billion year and specific activity of 4.1×10^6 Bqkg^{-1}. The isotopes of thorium such as ^{228Th} constitutes only about 1.35×10^{-8} percent of total thorium in nature and the rest such as ^{234}Th, ^{230}Th, ^{231}Th as exist at extremely small amounts (UNSCEAR, 2000). The radionuclide ^{228}Ra has a sufficient long half-life that may allow some separation from its parent, ^{232}Th. The gaseous element of the chain, ^{220}Rn, has a very short half-life and no long-lived decay products with the final most stable decay product being ^{208}Pb.

Natural potassium has 3 isotopes: ^{30}K, ^{40}K and ^{42}K; among them, the only isotope of interest is the unstable ^{40}K with half-life of 1.2×10^9 years. It possesses natural gamma radioactivity and its abundance in nature is 0.0118% of all potassium present in the earth crust. During decay ^{40}K produces two daughter isotopes; decay to give ^{40}Ca and or electron capture to ^{40}Ar (Argonne National Laboratory, EVS Human Facts Sheet, 2005).

2.3 Naturally Occurring Ionizing Radiation in Environment

According to the UNSCEAR, 2000 report to the general assembly, the ionizing radiation from natural sources is continually bombarding every object on the surface of earth. These natural radiations from high-energy cosmic ray particles from space in earth's atmosphere and those radioactive nuclides originating from the earth's crust and are present everywhere in the environment including the human body. The human body therefore is exposed to both external and internal radiations arising from these sources. At times people are exposed unintentionally to enhanced levels of the natural radiation at their places of work. Such workers include underground miners and some workers involved in processing of minerals that may contain enriched sources of such radiation. Cosmic rays interact with the nuclei of atmospheric constituents, producing a cascade of interactions and secondary reaction products that contribute to enhanced cosmic ray exposures. The interaction could decrease the intensity of some specific radiations with short half-life with depth in the earth's atmosphere to ground level. The cosmic ray interactions also produce a number of radioactive nuclei known as cosmogenic radionuclides and the best examples of these are ^{3}H and ^{14}C. Naturally occurring radionuclides of terrestrial origin (also called primordial radionuclides) are present in

various degrees in all media in the environment, including the human body itself. Only those radionuclides with half-lives comparable to the age of the earth, and their decay products, exist in significant quantities in these materials. The penetration of the human body from external sources is mainly by gamma radiation from radionuclides in the ^{238}U and ^{232}Th series and from ^{40}K. These radionuclides are also present in the body and irradiate the various organs with alpha and beta particles from within as well as gamma rays, some other terrestrial radionuclides, those of the ^{235}U series, ^{87}Rb, ^{138}Sm and ^{176}Lu, exist in nature but at such low levels that their contributions to the dose in humans are small (UNSCEAR, 2000).

2.4 Specific Activity

The amount of radiations from a source depends on number of disintegrations of unstable nuclei in the source of radiation. The rate of disintegration gives the rate at which individual radiations are emitted from the source. This also gives the rate of fragmentation of unstable nuclei. Therefore the amount of radiation from a radioactive nuclide is measured as number of disintegrations per second, the unit of which is Becquerel (Bq). The strength of radiation from a source is measured in the units of Becquerel. Its intensity depends on number of unstable nuclei or simply mass of the material containing the radioactive nuclide. The intensity of radiation by a unit mass is called specific activity or activity concentration of the source of radioactivity and is calculated using the formula specific activity,

$$As = \frac{N}{mCt} \hspace{4cm} 2.1$$

where N = total net counts of a radionuclide in a radioactive sample or source

m = mass of the sample

t = acquisition time

C = correction coefficient of the detector for a radionuclide

As = specific activity

The intensity of radiation from different materials is thus measured in terms of specific activities of the materials in Bqkg^{-1}. The specific activities simply give number of radiations evolved from a unit mass of the material and do not give the nature of radiations evolved. However, each radionuclide could give different types of radiations which have different effects on materials exposed to them. The gamma radiations emitted by different nuclides will also have different specific activities. There are important measurements that have been done to determine activity concentrations for different materials that contain radioactive nuclides.

Turhan et al. (2012), assessed the distribution of terrestrial and anthropogenic radionuclides in Turkish surface soil samples, the specific activities of the radionuclides ^{238}U ranged from 2.0 Bqkg^{-1} to 220.0 Bqkg^{-1} with the mean of 28.8 Bqkg^{-1} $\pm$ 0.7 Bqkg^{-1}, that of ^{232}Th ranged from 1.0 Bqkg^{-1} to 158.6 Bqkg^{-1} with mean of 33.0 Bqkg^{-1}$\pm$ 0.7 Bqkg^{-1} while that of ^{40}K ranged from 26.0Bqkg^{-1} to 1603 Bqkg-^{1} with mean of 448.5 Bqkg^{-1} $\pm$ 7.3Bqkg^{-1}.

Faanu et al. (2016), determined natural activity levels in soils, rocks and water at a mining concession of perseus gold mine and surrounding towns in the central region of Ghana. The results of the study show that the mean specific activity in soils and rocks of ^{238}U was 65.1 Bqkg^{-1}$\pm$ 2.2 Bqkg^{-1}, that of ^{232}Th was 71.8 Bqkg^{-1}$\pm$ 2.2 Bqkg^{-1} and that of ^{40}K was 1168.3 Bqkg^{-1}. All the values obtained were above the world wide average values of 35 Bqkg^{-1}, 30 Bqkg^{-1} and 400 Bqkg^{-1} for ^{238}U, ^{232}Th and ^{40}K respectively.

Turyahabwa,S . E. R. (2016), determined natural radioactivity levels due to mines Tailings from the selected mines in Southwestern Uganda and found out that the specific activities of ^{238}U, ^{232}Th, and ^{40}K ranged from 35.5 Bqkg^{-1} to 147.0 Bqkg^{-1}, 119.3 Bqkg^{-1} to 376.7 Bqkg^{-1} and 141.0 Bqkg^{-1} to 1658.5 Bqkg^{-1}. The results obtained above were more than the world wide average values of 35 Bqkg^{-1}, 30 Bqkg^{-1} and 400 Bqkg^{-1} for ^{238}U, ^{232}Th and ^{40}K respectively (UNSCEAR, 2000)

2.5 Absorbed dose

Absorbed dose is a measure of the energy deposited in a medium by ionizing radiation. It is equal to the energy deposited per unit mass of the medium so has the unit Jkg^{-1} or Gray. The absorbed dose is used to assess the potential for biochemical changes in specific tissues. It is calculated using equation 2.2 (UNSCEAR, 2000)

$$D = 0.462A_U + 0.604A_{Th} + 0.0417A_K \; (nGyh^{-1}) \hspace{3cm} 2.2$$

where: A_U, A_{Th} and A_K are activity concentrations of ^{238}U, ^{232}Th, and ^{40}K respectively.

      D is the absorbed dose rate

The estimation assumes a uniform distribution of the natural occurring radionuclides in the rock, tailings and soil samples. There are numerous studies that have been done to find the absorbed dose rate in different materials found in the environment.

Davou et al. (2015), carried out evaluation of radiation hazard indices due to natural radioactivity in mine tailings in some locations in Jos Plateau State of Nigeria. The results of the study show that the absorbed dose varied from 3559.09 $nGyh^{-1}$ to 18178.44 $nGyh^{-1}$ far above the world wide average of 60 $nGyh^{-1}$ (UNSCEAR, 2000).

Turyahabwa, S. E. R. (2016), determined the absorbed dose in mine tailings from Mashonga gold mine southwestern Uganda and found out that the average absorbed dose was 181.2 ± 66.8 $NGyh^{-1}$ far above the world average of 60 $nGyh^{-1}$.

Zakari et al. (2013), determined the absorbed dose around Birnin Gwari Artisanal Gold mine, Kaduna State, and found the average absorbed dose to be 96.52 $nGyh^{-1}$ which was more than the world wide average value.

2.6 Annual effective dose equivalent

The absorbed dose is not a good indicator of the likely biological effect; the risk of stochastic effect due to radiation exposure for the population can be quantified using the effective dose to each organ depending upon its radio-sensitivity. The severity of any

radiological hazard is estimated based on the annual radiation dose received by a person working or living in the radiation environment.

To estimate the annual effective dose outdoor, the conversion coefficient from absorbed dose in air to effective dose outdoor and indoor occupancy factors is always taken into account. The dose rate data obtained from the concentrations of natural radionuclides in samples are used, the 0.7 SvGy^{-1} conversion factor for absorbed dose rates in air to effective dose received by adults is adopted and it is assumed that people in study area on the average, spent 20% of their time outdoor, and 80% indoor, the Annual Effective Dose Equivalent outdoor (AEDE) is calculated using the equation 2.3 (UNSCEAR, 2000)

$$AEDE = D \times CF \times OF \times T \qquad\qquad 2.3$$

Where D is the absorbed dose rate in air

CF is dose conversion factor (0.7SvGy-1)

OF is the outdoor occupancy factor (0.2)

T is time factor (8766 h for a leap year or 8760 h for an ordinary year)

A number of important studies have been done to measure the annual effective dose equivalent in different environmental samples and the following results among others have been obtained.

Turyahabwa, S. E.R . (2016), determined annual effective dose equivalent in gold mine tailings from Mashonga in Southwestern Uganda and found out the mean value to be 0.37± 0.14 mSvy^{-1}. The average value obtained in this study is close to the world wide average value of 0.41 mSvy^{-1}.

Zakari et al. (2013), determined the annual effective dose equivalent around Birnin Gwari Artisanal Goldmine, Kaduna State, Nigeria and found the average value of annual effective dose equivalent to be 0.675 mSvy^{-1} greater than the world wide average.

Faanu, et al. (2016), determined annual effective dose equivalent in soil and rocks at a mining concession of Perseus gold mine and surrounding towns in the central region of Ghana. The average annual effective dose equivalent was found to be 0.918 mSvy^{-1} greater than the world wide average value. This therefore points to the fact that there are mines with high radiation levels in different parts of the world; therefore, knowledge of the radiation levels in the environment becomes apparent so that proper mining regulatory policies are formulated to protect the miners and the environment.

2.7 Hazard indices

The likelihood of a person developing radiological related illnesses such as respiratory diseases like as asthma, cancer and external diseases which may include skin cancer, erythema and cataracts when exposed to a certain amount of dose of ionizing radiation is quantified using Internal Hazard Indices (H_{in}) and External Hazard Indices (H_{ex}) respectively (Taskin et al .2009). When H_{in} and H_{ex} are less than one then, it means that the radiation hazard is considered negligible. The external and internal radiological hazard indices of the NORM in radioactive samples are determined using equations 2.4 and 2.5 based on the specific activities of ^{226}Ra, ^{232}Th and ^{40}K nuclides (Ramasamy et al . 2009).

External hazard indices, $H_{ex} = (A_{Ra} /370) + (A_{Th} /259) + (A_K /4810) \leq 1$ 2.4

Internal hazard indices, $H_{in} = (A_{Ra} / 185) + (A_{Th} /259) + (A_K / 4810) \leq 1$ 2.5
where $A_{Ra,}$ A_{Th} and A_K are the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K (Bq/kg) respectively. A number of studies have been done in different parts of the world to determine the values of hazard indices in different environment samples.

Caspah et al. (2016), carried out assessment of radiological hazard from Gold mine tailings in the Province of Gauteng in South Africa, the results of the study show that the average values of external and internal hazard indices were 2.4 and 4.5 respectively greater than the maximum permissible limit of unity set by ICRP, 1999.

Faanu et al. (2016), determined the internal and external hazard indices in soil and rock samples at a mining concession of Perseus gold mine and the surrounding towns in central Region of Ghana and found out that the average values of internal and external indices were 0.9 ± 0.1 and 0.7 ± 0.2 respectively. The values obtained were very close to the maximum permissible limit set by ICRP.

Davou, L. (2015), carried out an evaluation of radiation hazard indices due to naturally radioactivity in the mine tailings in some locations in JOS Plateau State of Nigeria and found out that the internal and external hazard indices ranged from 24.17 to 114.70 and 21.94 to 112.34 respectively. The results obtained were far beyond the maximum permissible limits set by ICRP.

2.8 Excess Lifetime Cancer Risk

The Excess Lifetime Cancer Risk (ELCR) is also a measure which is used to predict the likelihood that a person who is free of certain type of cancer will develop or die of that type of cancer during his or her lifetime. This can be estimated using the ICRP methodology shown in equation 2.7 (ICRP, 1999)

$$ELCR = AEDE \times DL \times RF \qquad\qquad 2.6$$

where AEDE is the total Annual Effective Dose Equivalent, DL the duration of Life (70 years) and RF the fatal cancer risk per Severt (Sv^{-1}). Studies done using materials from the environment have shown that some regions of the world have values of ELCR above the worldwide average while others have low values below the worldwide average.

Avwiri et al. (2014), carried out a study to determine Excess Lifetime Cancer Risk in the soil, sediment and water around mini- Okoro/Oginiba Creek Port Harcourt, River state, Nigeria. It was found out that the Excess Life time Cancer Risk in the sediment ranged from 0.006×10^{-3} to 0.021×10^{-3}, 0.002×10^{-3} to 0.009×10^{-3} and 0.014×10^{-3} to 0.048×10^{-3} respectively which were lower than the worldwide average of 0.29×10^{-3} (UNSCEAR, 2000).

Davou, L.C. (2015), carried out evaluation of excess lifetime cancer risk due to natural radioactivity in mine tailings in some locations in Jos Plateau State of Nigeria and found out the excess lifetime cancer risk values ranged from 0.15277×10^{-3} to 0.78029×10^{-3}. The results were higher the world wide average.

2.9 Biological Effects of Radiation

The knowledge of radionuclides distribution and radiation intensity in the environment is important for assessing the effects of radiation exposure due to both terrestrial and extra-terrestrial sources to the human population (El-Arabi, 2007). Radioactive materials decay spontaneously and produce ionizing radiation, which can have sufficient energy to strip away electrons from atoms creating two charged ions or to break some chemical bonds. Therefore, any living tissue in the human body can be damaged by ionizing radiation in a unique manner. All ionizing radiations cause similar damage at cellular level. The fact that beta (β) and alpha (α) particles are relatively not penetrative, external exposure to α and β does not cause a lot of damage however, they become more dangerous when swallowed or inhaled because they carry more energy and would irradiate the living tissues directly and deposit their energies. The penetrative power of gamma radiation makes it to be absorbed in the body and thus can easily cause radiation effects according to Ghose et al. (2012). It is worthwhile to note that exposure to the radiation doses should be kept As Low As Reasonable Achievable (ALARA).

Alpha Radiation (Alpha Particle) is a particle, consisting of two protons and two neutrons that travels very fast and thus has a good deal of kinetic energy. The protons give it a large positive charge that pulls hard at the electrons of other atoms it passes near. When the alpha particle passes near an atom, it excites its electrons and can pull an electron from the atom, which is the process of ionization. Each time the alpha particle pulls an electron off from an atom in its path, the process of ionization occurs. With each ionization, the alpha particle loses some energy and slows down. It will finally take two electrons from other atoms at the end of its path and become a complete helium atom which has no effect on the body. Alpha particles ionize tissue very strongly because of their large mass and charge. If the alpha particle is from radioactive material that is

outside the body, it will lose all its energy before getting through the outer (dead) layer of the human skin. This means that one can only be exposed to alpha radiation if the radioactive material that produces alpha radiation is taken into the body by breathing it in or swallowing it in food or drink. Once inside the body, this radioactive material can be mixed with the food in the stomach and intestines, then absorbed into the blood, incorporated into a molecule, and finally deposited into living tissue such as the bone matrix. The alpha particles from this radioactive material can cause damage to the tissue in which it is absorbed through direct interaction when the source is within the tissue (UNSCEAR, 2000).

Beta radiation or beta particles are high-energy electrons that some radioactive materials emit when they disintegrate. Beta particles are produced as a result of a neutron breaking up into a proton and an electron. However, the breaking up of a proton on the other hand ends up in production of a positron similar to electron but has positive charge. The production of either positron or electron referred to as beta particle with a positive charge or a negative charge, involves disintegration of particles within the nucleus (UNSCEAR, 2000). Beta particles are the commonly formed radioactive particles involved in radioactivity and are negatively charged. They are much lighter and much more penetrating than alpha particles. Their penetrating power depends on their energy. Some, such as those from tritium, have very little energy, and can't pass through the outer layer of dead skin. Most have enough energy to pass through the dead outer layer of a person's skin and irradiate the live tissue underneath. One can also be exposed to beta radiation from within if the beta emitting radionuclide is taken into the body. A beta particle loses its energy by exciting and ionizing atoms along its path. When all of its kinetic energy is spent, a negative beta particle (negatron) becomes an ordinary electron and has no more effect on the body. A positron collides with a nearby negative electron, and this electron positron pair turns into a pair of gamma rays called annihilation radiation, which can interact with other molecules in the body.

Gamma Radiation (Gamma Rays) is produced when a radioactive atom transforms by giving off an alpha or a beta particle. An excited nucleus on its own can also give off one or more gamma rays to release any excess energy. Gamma rays are bundles of energy

that have no charge or mass. This allows them to travel very long distances through air, body tissue, and other materials. They travel so much farther than either alpha or beta radiation that the source of the gamma rays doesn't have to be inside the body or near the skin. A gamma ray may pass through the body without hitting anything, or it may hit an atom and give that atom all or part of its energy. This normally knocks an electron out of the atom and ionizes it. This electron then uses the energy it received from the gamma ray to ionize other atoms by knocking electrons out of them as well. Since a gamma ray is pure energy, once it loses all its energy, it no longer exists. Therefore, the main external source of irradiation to the human body is represented by the gamma radiation emitted by naturally occurring radioisotopes, also called terrestrial radionuclides (UNSCEAR, 2000).

CHAPTER THREE: METHODOLOGY OF THE STUDY

3.1 Introduction

This study was experimental based one where samples were collected from four gold mines. A survey approach was earlier on done by physically exploring different mining sites in the district to identify the suitable mines to carry out the study. Simple Random sampling technique was used to generate the samples which were prepared for gamma ray spectrometry analysis done using sodium iodide scintillation detector. An IBM compatible computer connected to the detector helped in displaying the photo peaks of the radionuclides present in the samples and determination of the corresponding count rates.

3.2 Research Design

The study started with survey of six gold mines in Busia District which is one of the gold mining districts in Uganda having scanty radiological information; out of which only four mines were selected for the study. The four mines were selected basing on the distance of separation which was at least 1 km from each other and number of miners involved in the mining operation in each mine observed. The mines selected had at least ten miners and those with fewer miners were left out. A total of 32, 20 and 10 samples of soil, rock and mine tailings respectively were selected from the four gold mines on the basis of their availability. The samples were then taken to the radioisotopes laboratory in Makerere University for gamma ray spectrometry analysis where the activity concentration of ^{238}U, ^{232}Th and ^{30}K were determined. The descriptive research design in terms of determining only specific parameter values instead of finding relationship between values was the objective of this study. The typical parametric values were statistically reduced to obtain values of the activity concentrations, absorbed doses, annual effective doses, hazard indices and cancer risk levels of three radionuclides that were in the samples. The results were to provide data base values of the parameters for Agata, Okame, Busia 90 and Greenstone resource limited Gold mines in Busia District.

3.3 Samples Selection

 Soil, rock and mine tailings samples were obtained from Agata, Okame, Busia 90 and Greenstone resource limited gold mines in Busia District Eastern Uganda. Eight soil samples each weighing about one kilogramme were collected using simple random sampling technique within a radius of 100 m from each of the four gold mines; giving a total of thirty two (32) soil samples labeled with the name of the gold mine. Twenty (20) rock and ten (10) mine tailings samples each weighing about one kilogramme were collected randomly within the selected area of mines and labeled with the name of the gold mine . These samples were transferred into polythene bags to avoid cross contamination in each case. Sample collection was done within one day since the sampling sites were identified and determined during the survey.

The soil, rock and mine tailings samples were then taken to the laboratory for preparations and gamma ray spectrometry analysis.

3.4 Sample Preparation for Gamma Spectrometry Analysis

In the laboratory, each of the soil, mine tailings and rock samples was dried in an oven at a temperature of 110 $^{\circ}$C until all moisture was completely removed and left to cool overnight. Each sample was pulverized into a fine powder using a mortar and pestle, and sieved through a 500 μm pore size mesh to obtain homogenous sample. Marinelli beakers of volume 500 ml and known masses were filled with the samples whose volumes were equal to that of the beakers and the mass, m, of each sample determined. The beakers with the samples were hermetically sealed to ensure that the radon gas confined within the volume and the decay products remain within the volume. The beakers were stored for four weeks for the short-lived daughters of radionuclides ^{238}U and ^{232}Th to attain secular equilibrium with their long-lived parent radionuclides (Turhan et al. 2007).

3.5 Measurement of Specific Activity of Radionuclides

The NaI (TI) detector system (GDM-20) was used for detection of the gamma energy from radioactive nuclides in samples. The set up was arranged as shown in Figure 3.1.
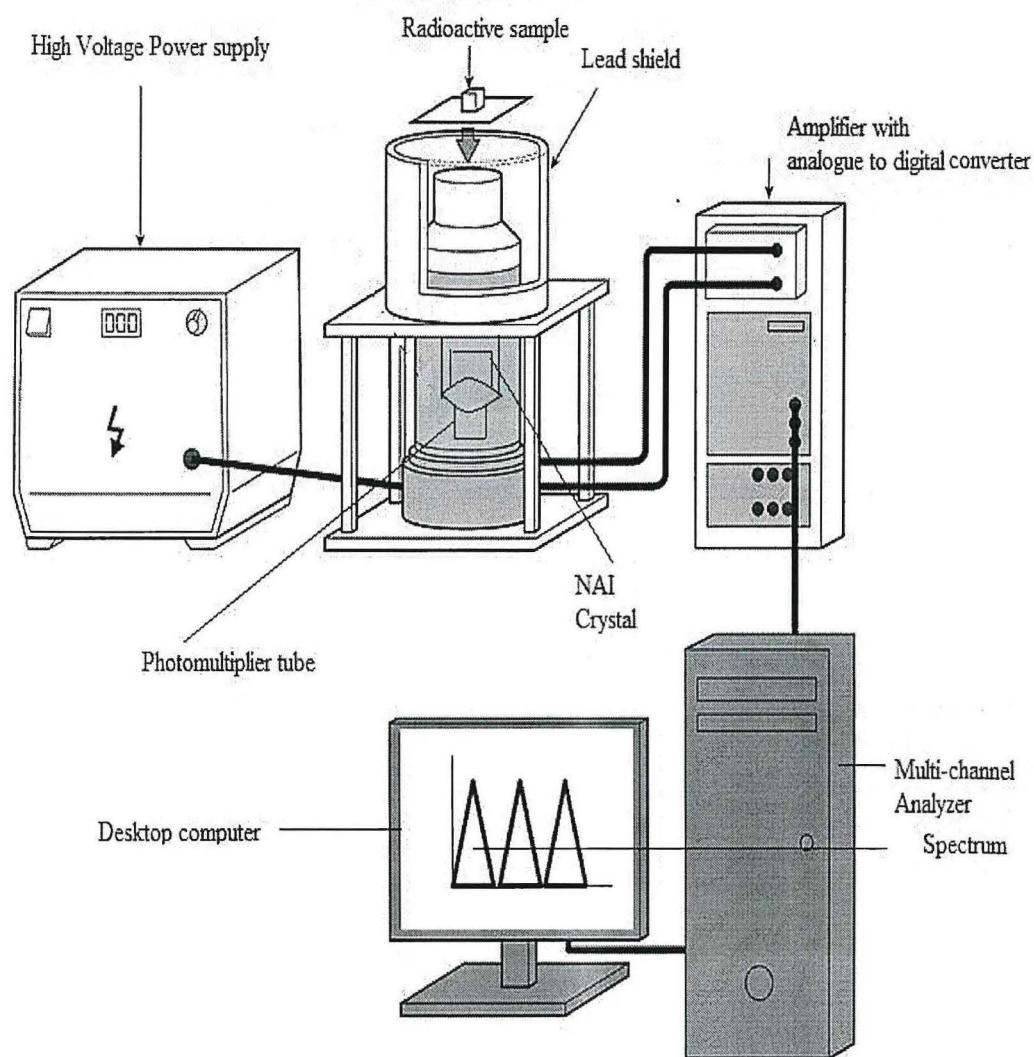
Source: Hakim, A. S. (2017)

Figure 3. 1: Experimental Set up of GDM – 20 System

The detector used was a scintillation detector consisting of cylindrical NaI crystal with a height and a diameter of 7.5cm. When each sample is put in the detector, the gamma radiation hits the crystal, creating a weak light which is converted to electrical pulses by a photomultiplier tube (PM). The pulses are amplified in an amplifier. An Analogue to

Digital converter converts the size of the pulses to digital information, which is processed by the computer. The detector and amplifier box are connected via an interface to an IBM compatible computer. The detection of the gamma radiation, data processing and presentation in from of a spectrum is performed by the software of the system.

The system was left on for a period of 6000s to allow gamma ray spectrum of the radionuclides contained in each sample to build up on the screen. The background radiation distribution in the environment around the detector gave rise to the background spectrum; this was used to correct the net peak area of gamma rays of measured isotopes by subtracting the background spectrum from the spectrum obtained.

The spectra obtained for different samples during the measurements were used to determine the radionuclides ^{232}Th, ^{238}U and ^{40}K which were identified from the photo peaks of their corresponding daughter radionuclides at different energies. ^{232}Th was identified in the laboratory from the average energies of 238keV of ^{212}Pb and 580kev of ^{208}Tl which are its daughter radionuclides. Similarly, ^{238}U was identified from the average energies of 295keV of ^{214}Pb and 352 keV of ^{214}Pb which are its daughter radionuclides. ^{40}K was identified from average energy of 1460keV. The spectra containing photo peaks of ^{238}U and ^{232}Th daughter products and ^{40}K were then analyzed basing on the assumption that secular equilibrium was established between the long-lived parent radionuclides ^{232}Th and ^{238}U, and their short lived daughter radionuclides. The total net counts, N under each of the most prominent photo peaks of ^{238}U and ^{232}Th daughters and ^{40}K peak were determined. The Specific Activity (As) was then calculated using the Equation (2.1) in Bqkg^{-1}. The values of the specific activities obtained were used to determine radiological parameters; absorbed dose rate, annual effective dose, hazard indices and excess lifetime cancer risk.

3.6 Presentation and treatment of data

The average specific activities of the data obtained for soil, mine tailings and rock samples were calculated. Basic descriptive statistics was used to illustrate the distributions of the three radionuclides identified and radiological hazard levels in soil,

mine tailings and rock samples from the four gold mines. Statistical parameters such as mean, standard deviation, maximum sampling error at 95%, F-ratio and theoretical values of F-distribution at 5% level of significance were obtained. The F-values were used to establish whether there were significant variations in the mean values of specific activities and radiological parameters among the gold mines. Bar charts to show variation of specific activities and radiological parameters in the four mines were drawn using Microsoft excel.

CHAPTER FOUR: RESULTS OF THE STUDY

4.1 Introduction

The spectrographs obtained for different samples analysed in this study were used to determine the specific activity, absorbed dose rates, annual effective dose equivalent, hazard indices in the different types of samples considered and the Excess lifetime Cancer Risk (ELCR) in each of the gold mines.

4.2 Specific Activity of Radionuclides in the gold mines

The specific activity (As) of the radionuclides in soil samples from the four gold mines under study were determined and values given in the Table 4.1.

Table 4. 1: Values of Specific Activity of Radionuclides in soil samples

Gold mine	Specific Activity/ Bqkg^{-1}		
	^{238}U	^{232}Th	^{40}K
Agata gold mine	16.3±1.2	58.0±5.2	57.3±16.5
Okame gold mine	31.9±4.3	87.6±9.0	179.7±46.2
Busia 90 gold mine	20.6±1.7	76.0±3.9	118.7±45.7
Greenstone resource limited gold mine	24.4±4.5	61.3±9.2	175.1±71.4
Mean	23.3	79.7	132.7
Standard deviation	2.9	11.9	49.7
Error at $\alpha = 0.05$	4.6	18.9	79.1
Worldwide average value	35	30	400
F-ratio	4.41	3.62	1.37
$F_{3,28}$ at $\alpha = 0.05$	2.96	2.96	2.96

From the Table 4.1, the average specific activity of ^{238}U in the soil samples from the four gold mines was 23.3 Bqkg^{-1} and ranged from 18.7 Bqkg^{-1} to 27.9 Bqkg^{-1}; for ^{232}Th, the average was 79.7 Bqkg^{-1} and ranged from 60.8 Bqkg^{-1} to 98.8 Bqkg^{-1} while that of ^{40}K ranged from 53.6 Bqkg^{-1} to 211.8 Bqkg^{-1} with a mean of 130.2 Bqkg^{-1}. All the above have been stated within 95% level of confidence. The specific activities of the radionuclides in the four mines were statistically different at $\alpha = 0.05$ with the exception

of that of ^{40}K. To compare the specific activities of radionuclides in the soil samples from the four gold mines, a bar chart of specific activity was drawn as shown in Figure 4.1.
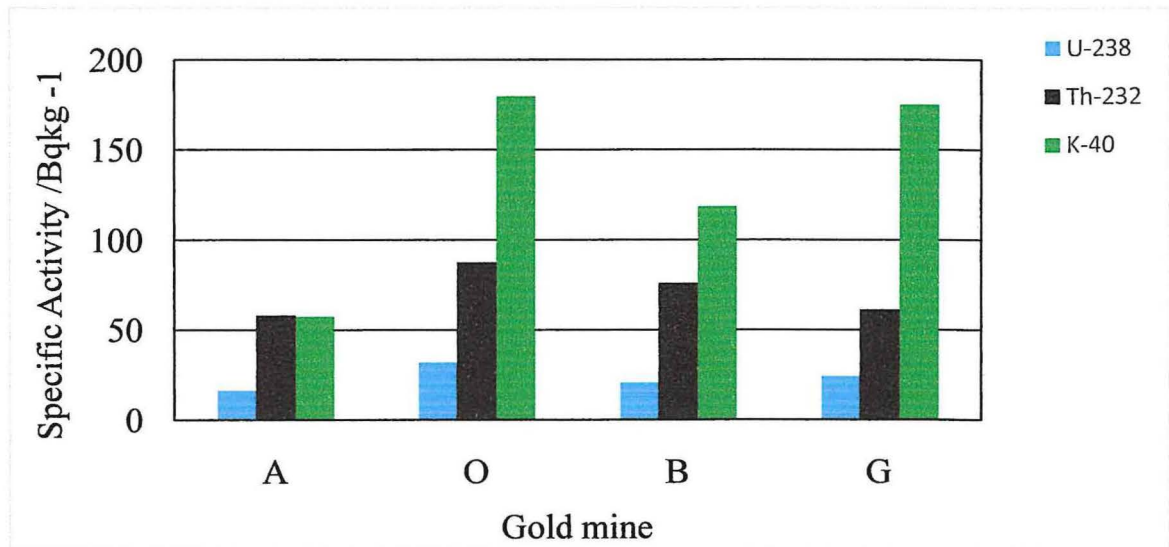
Figure 4. 1: A Bar Chart of Specific Activity of Radionuclides in soil samples

A = Agata mine; O = Okame Mine; B = Busia 90 gold Mine and G = Greenstone Resource limited gold mine. The Figure 4.1 shows that the specific activity of ^{40}K for each mine was highest followed by ^{232}Th and ^{238}U in all the four gold mines with the exception of Agata gold mine where the specific activity of ^{232}Th was greater than that of ^{40}K which was also greater than that of ^{238}U.

Okame gold mine according to Figure 4.1 had the highest specific activity of ^{40}K followed by Greenstone resource limited, Busia 90 and lastly Agata gold mine.

It is further noted from Figure 4.1 that the highest value of specific activity of ^{232}Th was registered in Okame soil samples followed by Busia 90, Greenstone resource limited and lastly Agata gold mine.

From Figure 4.1, it is observed that the highest value of specific activity of ^{238}U was obtained in soil samples from Okame gold mine followed by Greenstone resource limited, Busia 90 and lastly Agata gold mine.

The specific activity of the radionuclides in the mine tailings samples from the four gold mines under study were determined and values given in the Table 4.2.

Table 4. 2: Values of Specific Activity of Radionuclides in Mine tailings samples

Mines	Specific activity/ Bqkg^{-1}		
	^{238}U	^{232}Th	^{40}K
Agata gold mine	11.7±2.3	32.3±1.8	219.2±57.0
Okame gold mine	10.8±1.5	26.5±3.9	37.3±12.6
Busia 90 gold mine	12.0±9.1	26.8±18.6	98.9±81.2
Greenstone resource limited gold mine	15.5±0.8	44.8±5.5	90.6±36.0
Mean	10.3	28.9	111.5
Standard deviation	1.8	2.4	66.5
Error at α = 0.05	2.9	3.8	105.8
Worldwide average value	35	30	400
F-ratio	0.21	1.16	3.16
F$_{3,6}$ at α= 0.05	4.76	4.76	4.76

From the Table 4.2, the specific activity of ^{238}U, ^{232}Th and ^{40}K in the mine tailings samples were not significantly different for all the mines since F-ratio was less than theoretical value of F- distribution at α = 0.05. The average specific activities of ^{238}U ranged from 7.4 Bqkg^{-1} to 13. 2 Bqkg^{-1} with a mean of 10.3 Bqkg^{-1} while for ^{232}Th, it ranged from 25.1 Bqkg^{-1} to 32.7 Bqkg^{-1} with a mean of 28.8 Bqkg^{-1} and that of ^{40}K ranged from 5.7 Bqkg^{-1} to 217.3 Bqkg^{-1}with a mean of 111.5 Bqkg^{-1}. All the above values were stated within 95% level of confidence.

To compare the specific activity of radionuclides in the mine tailings samples from the four gold mines, a bar chart of specific activity was drawn as shown in Figure 4.2.
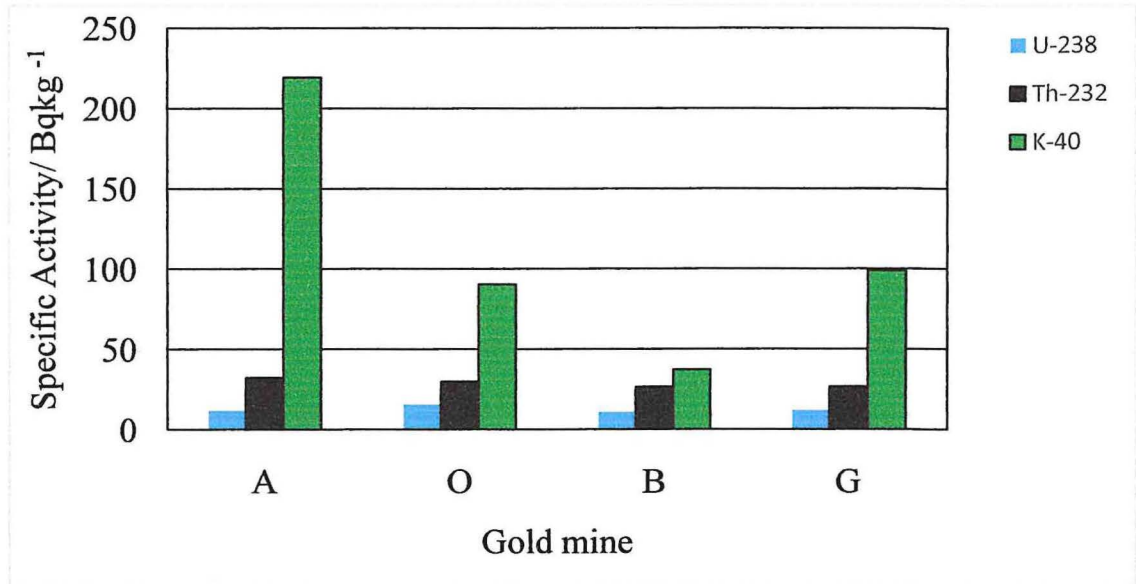
Figure 4. 2: A Bar Chart of Specific Activity of radionuclides in Mine tailings samples

As from Figure 4.2, the specific activity of ^{40}K was highest followed by ^{232}Th and ^{238}U in each of the four gold mines.

The specific activity of ^{40}K in the mine tailings samples from Agata gold mine according to Figure 4.2 was the highest followed by Greenstone resource limited, Okame and Busia 90 gold mine.

Figure 4.2 further showed that the specific activity of ^{32}Th in mine tailings samples was highest in Agata followed by Okame, Greenstone Resource limited and Busia 90 gold mine.

Fugure 4.2 also showed that the specific activity of ^{226}Ra was highest in mine tailings samples from Okame gold mine followed by Greenstone Resource limited, Agata and Busia 90 gold mine.

The specific activity of the radionuclides in the mine tailings samples from the four gold mines under study were determined and values given in the Table 4.3.

Table 4. 3: Values of Specific Activity of Radionuclides in rock samples

Mines	Specific activity/ Bqkg^{-1}		
	^{238}U	^{232}Th	^{40}K
Agata gold mine	1.7 ± 0.3	2.3 ± 1.1	2.1 ± 0.6
Okame gold mine	27.8±9.7	66.6±23.7	120.1 ±41.7
Busia 90 gold mine	3.2±0.8	6.0±3.3	36.8±18.0
Greenstone resource limited gold mine	2.9± 0.5	4.3±1.1	20.4±9.5
Mean	8.9	19.8	47.9
Standard deviation	10.9	27.1	43.8
Error at α = 0.05	17.3	43.1	69.7
Worldwide average value	35	30	400
F-ratio	6.65	6.79	5.03
$F_{3,16}$ at α= 0.05	3.23	3.23	3.23

From the Table 4.3, the specific activity of ^{238}U ranged from 1.7 Bqkg^{-1} to 27.8 Bqkg^{-1} with a mean of 8.9 Bqkg^{-1} while that of ^{232}Th ranged from 2.3 Bqkg^{-1} to 66.6 Bqkg^{-1} with a mean of 19.8 Bqkg^{-1} and that of ^{40}K ranged from 2.1 Bqkg^{-1} to 120.1 Bqkg^{-1} with a mean of 47.9 Bqkg^{-1}. The specific activities of the above radionuclides were significantly different at α = 0.05 since F-ratio was greater than $F_{3,\,6}$.

To compare the specific activity of radionuclides in the rock samples from the four gold mines, a bar chart of specific activity against gold mine was drawn as shown in Figure 4.3.
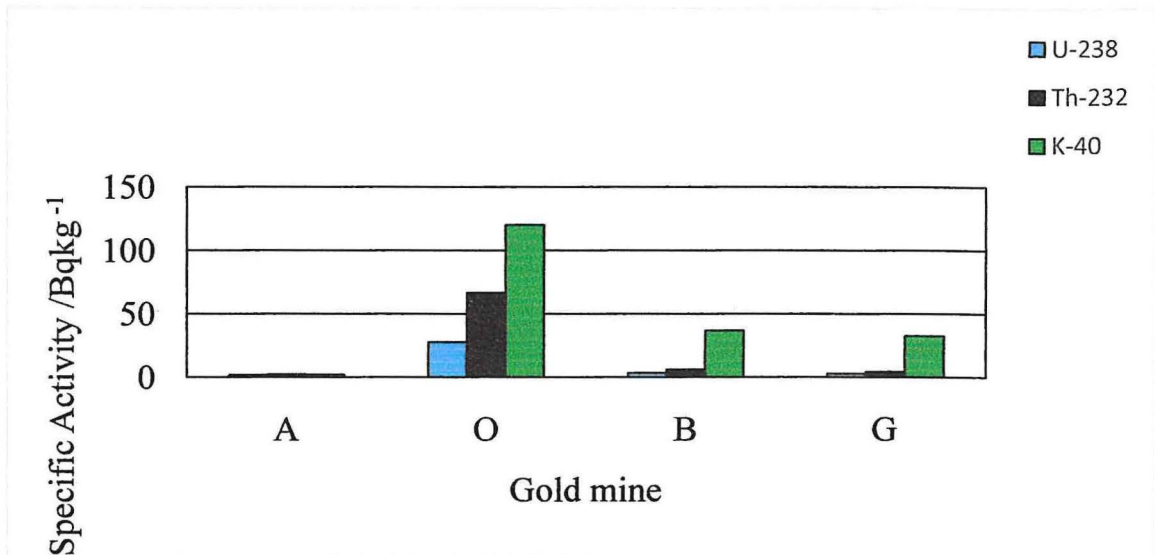
Figure 4. 3: A Bar Chart of Specific Activity of Radionuclides in rock samples

Figure 4.3 shows that the specific activity of ^{40}K was greater than that of ^{232}Th and that of ^{232}Th greater than that of ^{238}U in all the four gold mines with the exception of Agata gold mine where the activity concentration of ^{232}Th was greatest followed by that of ^{40}K and that of ^{238}U being the least. The specific activity of ^{238}U was highest in Okame gold mine rock samples followed by Busia 90, Greenstone resource limited, and lastly Agata gold mine while for ^{232}Th, the highest value registered was in Okame rock samples followed by, Busia 90 Greenstone resource limited and lastly Agata gold mine and for ^{40}K the highest value was obtained in rock samples from Okame gold mine followed by Busia 90, Greenstone resource limited and lastly Agata gold mine.

4.3 Absorbed Dose Rates (ADR) of Radionuclides in the gold mines

The external gamma dose rate from the soil, mine tailings and rock samples in outdoor air at 1m above the ground surface to the workers in the gold mines was calculated using Equation (2.2).

The absorbed dose rate of the radionuclides in the soil samples from the four gold mines under study were determined and values given in the Table 4.4.

Table 4. 4: Values of Absorbed Dose Rates of Radionuclides in soil samples

Mines	Absorbed Dose Rate/ nGyh^{-1}
Agata gold mine	44.9±3.4
Okame gold mine	75.1±8.8
Busia 90 gold mine	60.4±3.1
Greenstone resource limited gold mine	55.6±8.1
Mean	59.0
Standard deviation	10.9
Error at α= 0.05	17.3
Worldwide average value	60
F-ratio	3.82
$F_{3,28}$ at α= 0.05	2.96

Table 4.4 shows that the average absorbed dose rates in soil samples from the four gold mines were significantly different from the other since F-ratio was greater than $F_{3,28}$ at α = 0.05. The average value for the four mines was 59.0 nGyh^{-1} and within 95% level of confidence, it ranged from 41.7 nGyh^{-1} to 76.3 nGyh^{-1}. To compare the absorbed dose rates of radionuclides in the soil samples from the four gold mines, a bar chart of absorbed dose rate was drawn as shown in Figure 4.4.
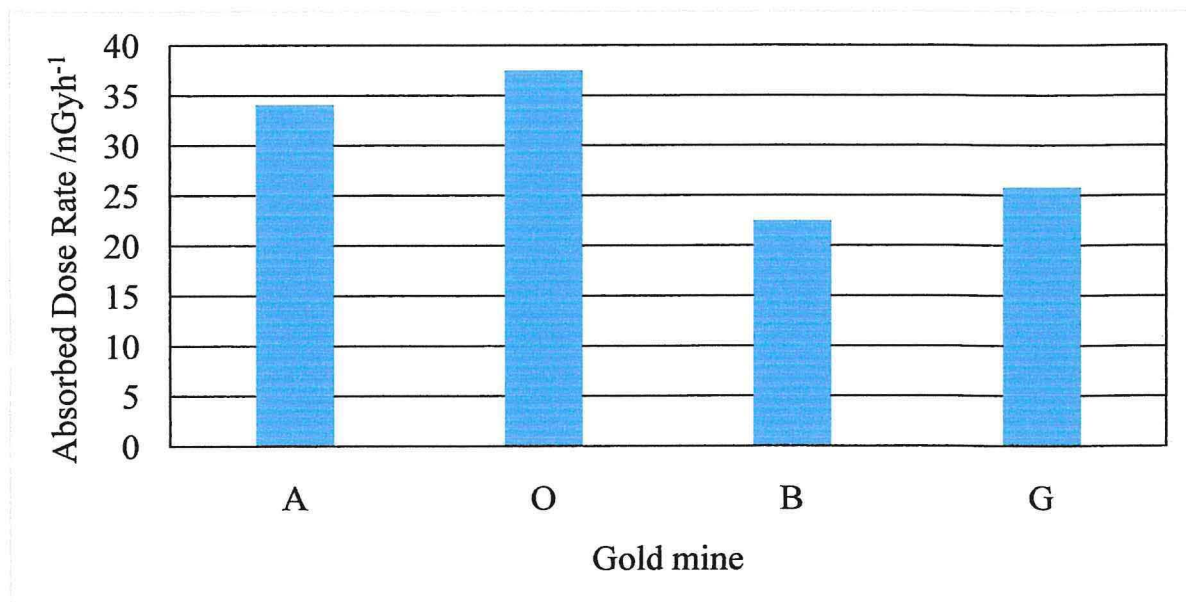
Figure 4. 4: A Bar Chart of Absorbed Dose Rates of Radionuclides in soil samples

Figure 4.4 shows that the highest absorbed dose rate was registered in soil samples from Okame gold mine followed by Busia 90, Greenstone resource limited and lastly Agata gold mine. The absorbed dose rate of the radionuclides in the tailings samples from the four gold mines under study were determined and values given in the Table 4.8.

Table 4. 5: Values of Absorbed Dose Rates of radionuclides in Mine tailings samples

Mines	Absorbed Dose Rate/ nGyh^{-1}
Agata gold mine	34.1±1.0
Okame gold mine	22.5±1.9
Busia 90 gold mine	25.8±18.8
Greenstone resource limited gold mine	38.0±4.5
Mean	23.0
Standard deviation	6.1
Error at α= 0.05	9.7
Worldwide average value	60
F-ratio	0.98
$F_{3,6}$ at α= 0.05	4.76

Table 4.5 shows that the mean absorbed dose rates in mine tailings samples were not statistically different for the four different mines since F-ratio was less than theoretical value of F-distribution at α = 0.05. Absorbed dose rates ranged from 13.3 nGyh^{-1} to 32.7

nGyh^{-1} within 95% level of confidence with a mean of 23.0 nGyh^{-1}. To compare the absorbed dose rates of radionuclides in the mine tailings samples from the four gold mines, a bar chart of absorbed dose rate was drawn as shown in Figure 4.5.
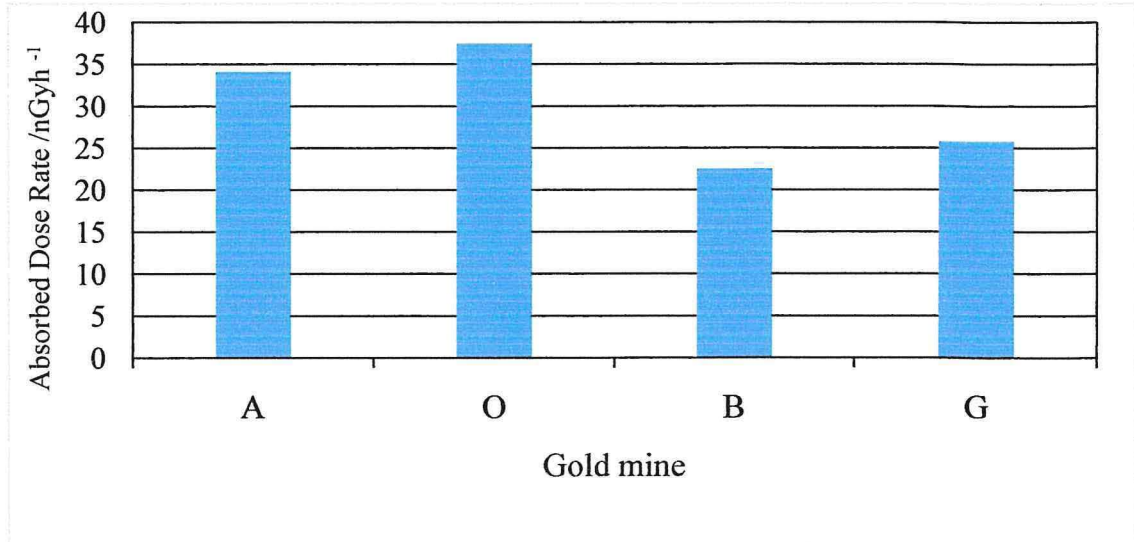
Figure 4. 5: A Bar Chart of Absorbed Dose Rates of Radionuclides in Mine tailings samples.

Figure 4.5 shows that the highest absorbed dose rate was registered in mine tailings samples from Okame gold mine followed by Agata, Greenstone resource limited and lastly Busia 90 gold mine.

The absorbed dose rates of the radionuclides in the rock samples from the four gold mines under study were determined and values given in the Table 4.6.

**Table 4. 6:** Values of Absorbed Dose Rates of radionuclides in rock samples from the Mines

Mines	Absorbed Dose Rate/ nGyh⁻¹
Agata gold mine	2.3 ± 0.8
Okome gold mine	58.0 ± 17.7
Busia 90 gold mine	6.3 ± 2.3
Greenstone resource limited gold mine	4.6 ± 1.0
Mean	17.8
Standard deviation	23.3
Error at $\alpha = 0.05$	37.1
Worldwide average value	60
F-ratio	9.0
$F_{3,16}$ at $\alpha = 0.05$	3.23

Table 4.6 shows that the absorbed doses rates in rock samples from the four gold mines were statistically different at $\alpha = 0.05$ with a mean of 17.8 nGyh⁻¹ ranging from 2.3 nGyh⁻¹ to 58.0 nGyh⁻¹ within 95% level of confidence. To compare the absorbed dose rates of radionuclides in the mine tailings samples from the four gold mines, a bar chart of absorbed dose rate was drawn as shown in Figure 4.6.
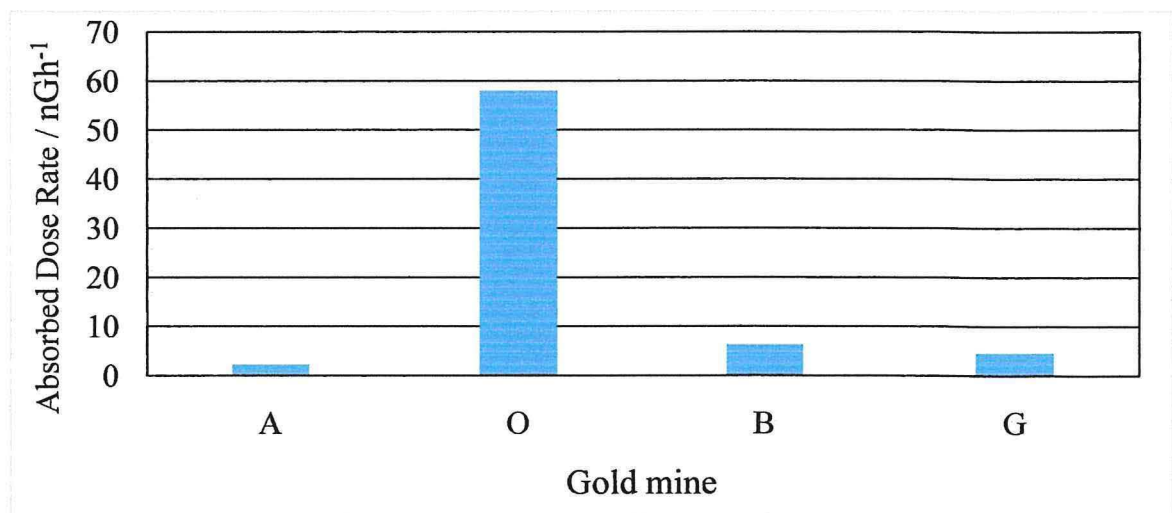
Figure 4. 6: A Bar Chart of Absorbed Dose Rates of Radionuclides in rock samples

Figure 4.6 shows that the highest value of absorbed dose rate was registered in Okame gold mine followed by Busia 90, Greenstone resource limited and Agata gold mine.

4.4 Annual Effective Dose Equivalent (AEDE) of radionuclides in the gold mines

The Annual Effective Dose Equivalent outdoor (AEDE) was calculated from equation 2.3. The annual effective dose equivalent of the radionuclides in the soil samples from the four gold mines under study were determined and found values given in the Table 4.7.

Table 4. 7: Values of Annual Effective Dose Equivalent of radionuclides in soil samples

Mines	Annual Effective Dose/ $mSvy^{-1}$
Agata gold mine	0.055±0.004
Okame gold mine	0.092±0.011
Busia 90 gold mine	0.074±0.004
Greenstone resource limited gold mine	0.068±0.010
Mean	0.072
Standard deviation	0.013
Error at $\alpha = 0.05$	0.021
Worldwide average value	0.41
F-ratio	3.79
$F_{3,28}$ at $\alpha = 0.05$	2.96

Table 4.7 shows that the annual effective doses in the soil samples from the four mines were statistically different from other since F-ratio was greater than the theoretical value of F distribution at $\alpha = 0.05$ and ranged from 0.051 $mSvy^{-1}$ to 0.093 $mSvy^{-1}$ with a mean of 0.072 $mSvy^{-1}$ within 95% level of confidence.

To compare the annual effective doses of radionuclides in the soil samples from the four gold mines, a bar chart of annual effective dose was drawn as shown in Figure 4.7.
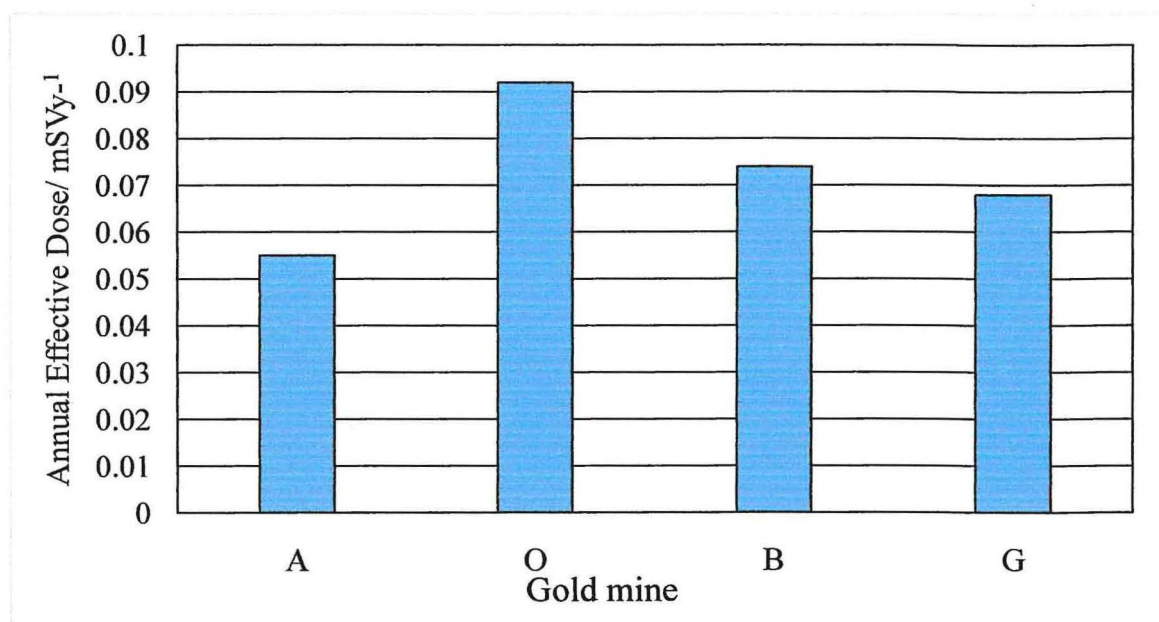
Figure 4. 7: A Bar Chart of Annual Effective Dose of Radionuclides in soil samples

Figure 4.7 shows that the highest value of annual effective dose was obtained in soil samples from Okame gold mine followed by Busia 90, Greenstone resource limited and Agata gold mine. The annual effective doses of the radionuclides in the mine tailings samples from the four gold mines under study were determined and values given in the Table 4.8.

Table 4. 8: Values of Annual Effective Dose of radionuclides in Mine tailings samples

Mines	Annual Effective Dose/ $mSvy^{-1}$
Agata gold mine	0.042±0.001
Okame gold mine	0.028±0.009
Busia 90 gold mine	0.032±0.023
Greenstone resource limited gold mine	0.046±0.006
Mean	0.037
Standard deviation	0.008
Error at $\alpha = 0.05$	0.013
Worldwide average value	0.41
F-ratio	0.83
$F_{3,6}$ at $\alpha = 0.05$	4.76

Table 4.8 shows that the annual effective doses in mine tailings samples from the four gold mines were not significantly different since F-ratio was less than the theoretical value of the F distribution at $\alpha = 0.05$ and they ranged from 0.024 mSvy^{-1} to 0.050 mSv with a mean of 0.037 mSvy^{-1} within 95% level of confidence.

To compare the annual effective doses of radionuclides in the mine tailings samples from the four gold mines, a bar chart of annual effective dose was drawn as shown in Figure 4.8.
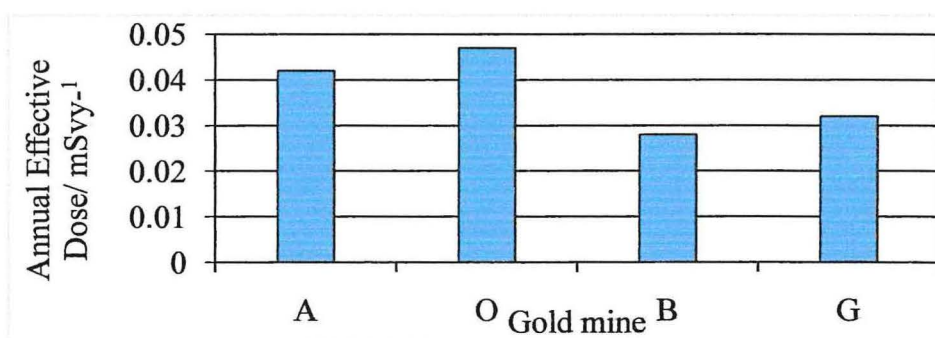
Figure 4. 8: A Bar Chart of Annual Effective Dose of Radionuclides in Mine tailings samples

The bar chart above shows that the highest value of annual effective dose was obtained in tailings samples from Okame gold mine followed by Agata, Greenstone resource limited and Busia 90 gold mine.

The annual effective doses of the radionuclides in the rock samples from the four gold mines under study were determined and values given in the Table 4.9.

Table 4. 9: Values of Annual Effective Dose of Radionuclides in rock samples

Mines	Annual Effective Dose/ $mSvy^{-1}$
Agata gold mine	0.011±0.008
Okame gold mine	0.081±0.017
Busia 90 gold mine	0.008±0.003
Greenstone resource limited gold mine	0.019±0.014
Mean	0.021
Standard deviation	0.018
Error at $\alpha = 0.05$	0.024
Worldwide average value	0.41
ICRP Recommended Value	20
F-ratio	8.87
$F_{3,16}$ at $\alpha = 0.05$	3.23

Table 4.9 shows that the annual effective doses in rock samples from all the four mines were statistically different since the F-ratio was greater than theoretical value of F-distribution at $\alpha = 0.05$ and ranged from 0.011 $mSvy^{-1}$ to 0.047 $mSvy^{-1}$ with a mean of 0.021 $mSvy^{-1}$. To compare the annual effective doses of radionuclides in the rock samples from the four gold mines, a bar chart of annual effective dose was drawn as shown in Figure 4.9.
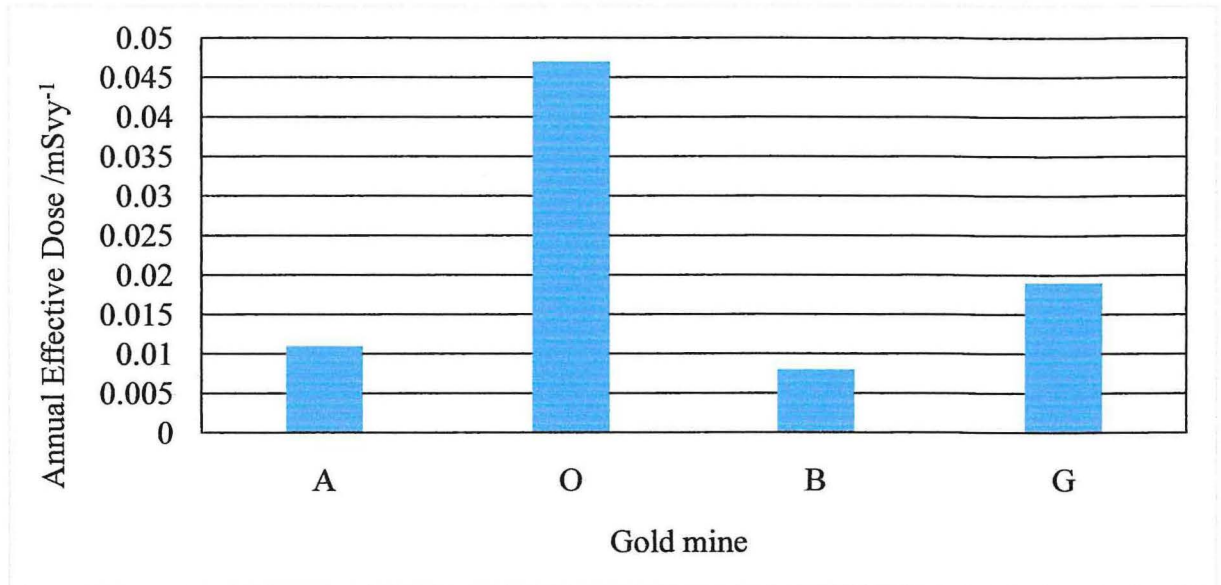
Figure 4. 9: A Bar Chart of Annual Effective Dose of Radionuclides in rock samples

Figure 4.9 shows that the highest value of annual effective dose was obtained in rock samples from Okame gold mine followed by Greenstone resource limited, Agata and Busia 90 gold mine.

4.5 Radiological Hazard Indices of Radionuclides in the gold mines

The external and internal radiological hazard indices of the NORM in the samples were determined using equations 4.4 and 4.5 based on the specific activities of ^{238}U, ^{232}Th and ^{40}K nuclides. The hazard indices of the radionuclides in the soil samples from the four gold mines under study were determined and values given in the Table 4.10.

Table 4. 10: Values of Hazard Indices of Radionuclides in soil samples

Mines	Internal Hazard Index	External Hazard Index
Agata gold mine	0.33±0.02	0.29±0.02
Okome gold mine	0.55±0.06	0.46±0.06
Busia 90 gold mine	0.43±0.02	0.38±0.02
Greenstone resource limited gold mine	0.41±0.06	0.34±0.05
Mean	0.43	0.37
Standard deviation	0.08	0.06
Error at $\alpha = 0.05$	0.13	0.10
ICRP Recommended Limit	≤ 1	≤ 1
F-ratio	3.82	3.08
$F_{3,28}$ at $\alpha = 0.05$	2.96	2.96

From Table 4.10, the hazard indices of radionuclides in the soil samples from all the four gold mines were statistically different from each other since the calculated F-value was more the theoretical value of the F distribution at $\alpha = 0.05$. The internal hazard indices in the soil samples ranged from 0.30 to 0.56 with a mean of 0.43.The external hazard indices ranged from 0.27 to 0.47 with a mean of 0.37. All the above are stated within 95% level of confidence. To compare the hazard indices of radionuclides in the soil samples from the four gold mines, a bar chart of hazard indices was drawn as shown in Figure 4.10.
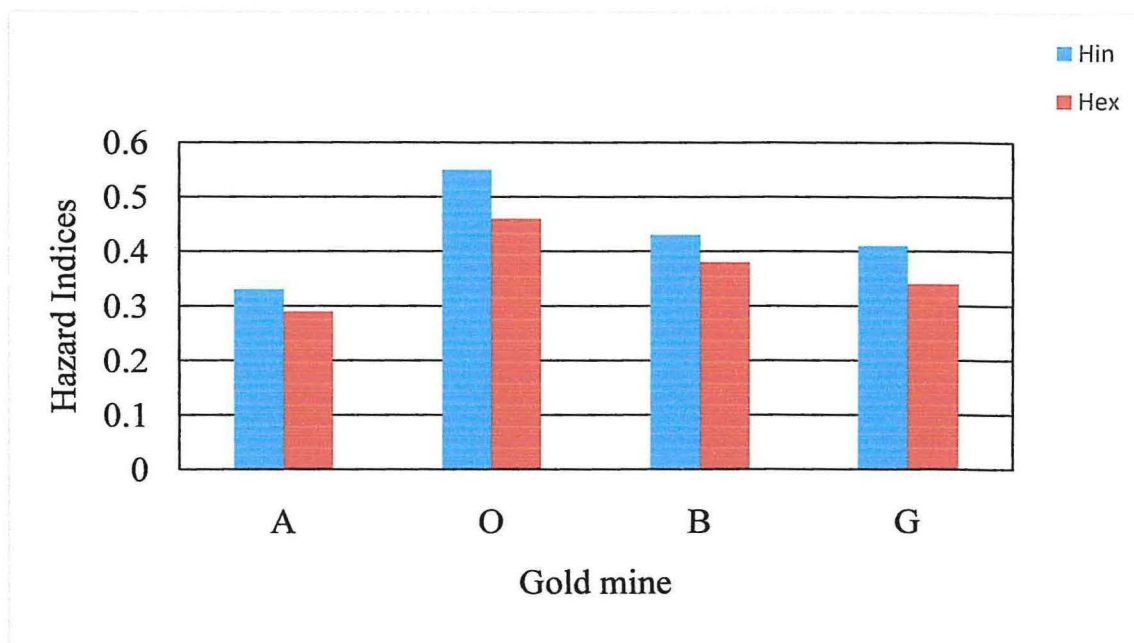
Figure 4. 10: A Bar Chart of Internal and External Hazard Indices of Radionuclides in soil samples

Figure 4.10 shows that the internal hazard index was higher than the external hazard index in each of the four mines with the highest value of internal hazard index obtained in soil samples from Okame gold mine followed by Busia 90, Greenstone resource limited and lastly Agata gold mine while the highest value of external hazard index was obtained in soil samples from Okame gold mine followed by Busia 90, Greenstone resource limited and lastly Agata gold mine.

The hazard indices of the radionuclides in the mine tailings samples from the four gold mines under study were determined and values given in the Table 4.11.

Table 4. 11: Values of Internal and External Hazard Indices of Radionuclides in Mine tailings samples

Mines	Internal Hazard Index	External Hazard Index
Agata gold mine	0.23±0.02	0.20±0.07
Okame gold mine	0.17±0.02	0.14±0.02
Busia 90 gold mine	0.19±0.14	0.16±0.12
Greenstone resource limited gold mine	0.28±0.03	0.24±0.03
Mean	0.21	0.19
Standard deviation	0.04	0.04
Error at $\alpha = 0.05$	0.06	0.06
ICRP Recommended Limit	≤ 1	≤ 1
F-ratio	0.69	0.84
$F_{3,6}$ at $\alpha = 0.05$	4.76	4.76

From Table 4.11, the hazard indices in the mine tailings samples in the four gold mines were not statistically different from the other since the calculated F-value was less than the table value. The internal hazard indices in the mine tailings samples ranged from 0.15 to 0.27 with a mean of 0.21 while the external hazard indices ranged from 0.10 to 0.23 with a mean of 0.19. All the above are stated within 95% level of confidence.

To compare the hazard indices of radionuclides in the mine tailings samples from the four gold mines, a bar chart of hazard indices was drawn as shown in Figure 4.11.
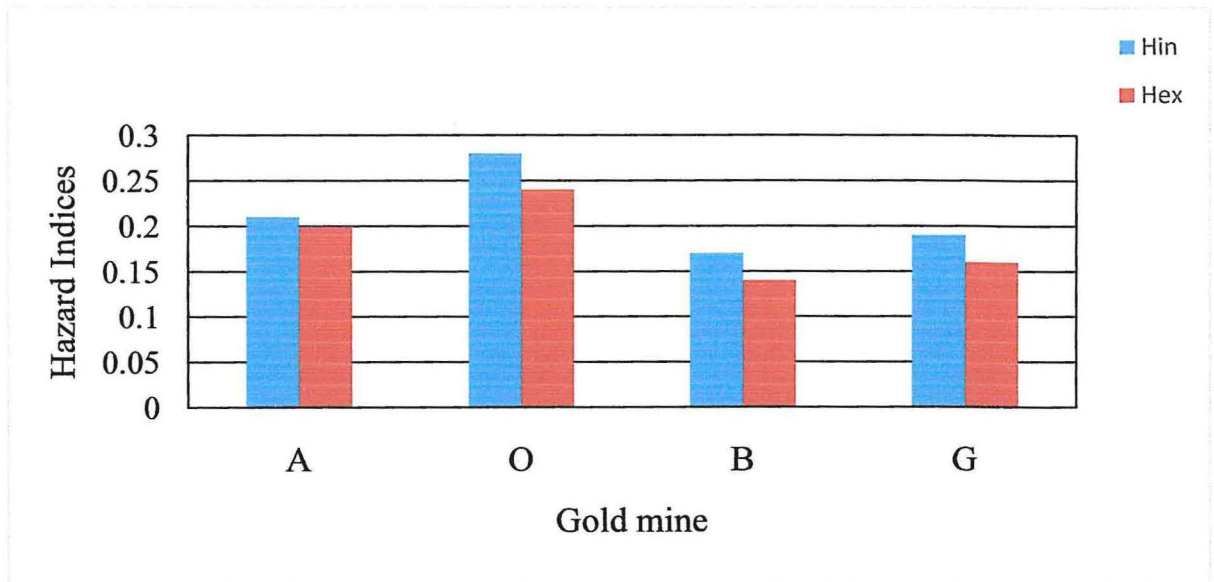
Figure 4. 11: A Bar Chart of Hazard Indices of Radionuclides in Mine tailings samples

Figure 4.11 shows that the internal hazard index in each of the four mines was higher than the external hazard index. The highest value of the internal hazard index was obtained in mine tailings samples from Okame gold mine followed by Agata, Greenstone resource limited, and lastly Busia 90 gold mine while the highest value of external hazard index was obtained in mine tailings samples from Okame gold mine followed by Agata, Greenstone resource limited and Busia 90 gold mine.

The hazard indices of the radionuclides in the rock samples from the four gold mines under study were determined and values given in the Table 4.12.

**Table 4. 12:** Values of Hazard Indices of radionuclides in rock samples

Mines	Internal Hazard Index	External Hazard Index
Agata gold mine	0.02±0.01	0.01±0.00
Okame gold mine	0.43 ±0.14	0.36 ±0.11
Busia 90 gold mine	0.05 ±0.02	0.02±0.01
Greenstone resource limited gold mine	0.04 ±0.01	0.03 ±0.01
Mean	0.14	0.11
Standard deviation	0.17	0.14
Error at $\alpha = 0.05$	0.27	0.22
ICRP Recommended Limit	≤ 1	≤ 1
F-ratio	0.11	0.14
$F_{3,16}$ at $\alpha = 0.05$	3.23	3.23

Table 4.12 shows that the hazard indices in the rock samples were not statistically different for all the mines since the calculated F-value was less than the table value of the F distribution at $\alpha = 0.05$. The internal hazard indices in the rock samples ranged from 0.02 to 0.43 with a mean of 0.14. The external hazard indices ranged from 0.01 to 0.36 with a mean of 0.11.

To compare the hazard indices of radionuclides in the rock samples from the four gold mines, a bar chart of hazard indices was drawn as shown in Figure 4.12.
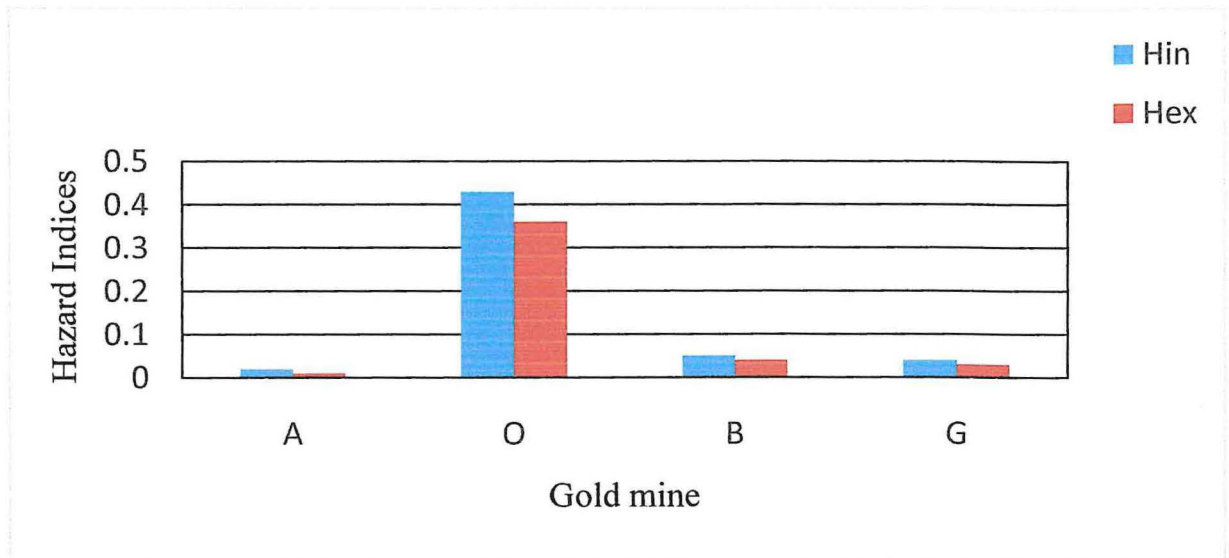
Figure 4. 12: A Bar Chart of Hazard Indices of Radionuclides in rock samples

Figure 4.12 shows that the internal hazard index in each of the four gold mines was higher than the external hazard index. The highest value of hazard index was obtained in rock samples from Okame gold mine followed by Busia 90, Greenstone resource limited, and lastly Agata gold mine while for the external hazard indices, the highest hazard index was obtained in rock samples from Okame gold mine followed by Busia 90, Greenstone resource limited and Agata gold mine.

4.6 Excess Lifetime Cancer Risk (ELCR) due to Radionuclides in the gold mines

According to the ICRP methodology, the Excess Lifetime Cancer Risk (ELCR) is calculated from the equation 2.6.

Table 4. 13: Values of Excess Lifetime Cancer Risk of Radionuclides

Gold mine	Excess Lifetime Cancer Risk/ $x10^{-3}$			
	Soil	Mine tailings	Rock	Average value
Agata	0.156±0.012	0.117±0.004	0.036±0.023	0.103±0.061
Okame	0.258±0.030	0.078±0.007	0.229±0.048	0.188±0.097
Busia 90	0.207±0.011	0.090±0.065	0.022±0.048	0.106±0.084
Greenstone resource limited	0.191±0.028	0.131±0.016	0.053±0.039	0.127±0.072
Mean	0.203	0.104	0.059	0.122
Standard deviation	0.042	0.024	0.097	0.039
Error at $\alpha = 0.05$	0.067	0.039	0.154	0.062
F-ratio	3.80	0.95	8.73	4.07
F at $\alpha = 0.05$	2.96	4.76	3.23	2.80

Table 4.13 shows that the values of the Excess Lifetime Cancer Risks were statistically different for all the mines since the F-ratio was greater than the theoretical value of F distribution at $\alpha = 0.05$. The mean ELCR to the workers was $0.122x10^{-3}$ and ranged from $0.060x10^{-3}$ to $0.184x10^{-3}$ within 95% level of confidence in all the mines. To compare the Excess Lifetime Cancer Risk of radionuclides in the four gold mines, a bar chart of ELCR was drawn as shown in Figure 4.13.
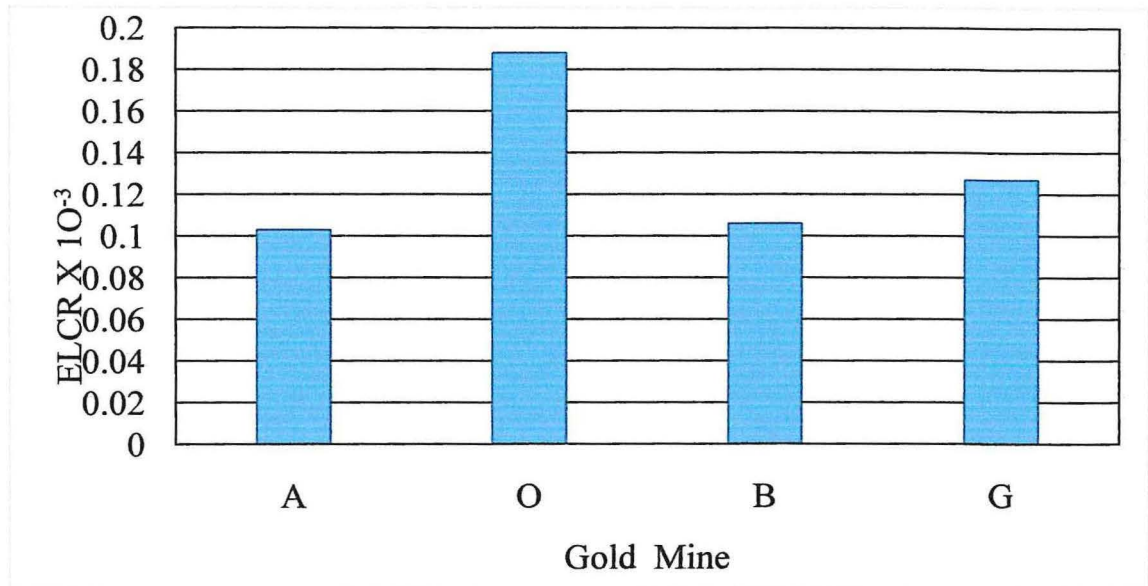
Figure 4. 13: A Bar Chart of Excess Lifetime Cancer Risk of radionuclides in the gold mines

Figure 4.13 shows that the cancer risk was highest in Okame gold mine followed by Greenstone resource limited, Busia 90, and Agata gold mine.

CHAPTER FIVE: DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 Discussion

At 95% level of confidence, the specific activity concentrations of ^{238}U in the soil samples for all the four gold mines ranged between 18.7 Bqkg^{-1} to 27.9 Bqkg^{-1} with a mean of 23.3 Bqkg^{-1}. This mean value is comparable with the value of 28.6 ± 0.9 Bqkg^{-1} in soil in Turkey as determined by Turhan et al. (2012). The calculated F–value (F$_{ratio}$= 4.41) for the data was greater than the theoretical value of the F- distribution (F$_{3, 28}$ = 2.96) at α = 0.05 level of significance implying that the mean values of ^{238}U were significantly different in all the four gold mines. The specific activity of ^{232}Th at 95% level of confidence ranged between 60.8 Bqkg^{-1} to 98.8 Bqkg^{-1} with a mean of 79.7 Bqkg^{-1}. This was comparable with the average value of ^{232}Th of 71.8±2.2 Bqkg^{-1} in soil and rock from Perseus gold mine-Ghana as determined by Faanu et al. (2016). The calculated F–value (F$_{ratio}$ = 4.41) for the data was greater than the theoretical value of the F- distribution (F$_{3, 28}$ = 2.96) at α = 0.05 level of significance implying that the mean values of ^{232}Th were significantly different in all the four gold mines. The significant variation in the specific activities of ^{238}U and ^{232}Th in the soil samples could be due to the difference in the concentrations of radioactive minerals such as Zircon , monazite, iron oxides, fluorite and others radioactive minerals in them which determine the distribution of uranium and thorium (Cuney et al.1987). In the case of ^{40}K, the activity concentrations at 95% level of confidence ranged between 53.6 Bqkg^{-1} to 211.8 Bqkg^{-1} with a mean of 132.7 Bqkg^{-1}. The calculated F–value (F$_{ratio}$=1.37) for the data was less than the theoretical value of the F- distribution (F$_{3, 28}$ = 2.96) implying that the mean values of ^{40}K were not significantly different in the four gold mines. The insignificant difference in the activity concentrations of the radionuclides in the soil samples could be due to the abundance of mineral such as feldspar, greensand and sylvite in the samples which determine concentration of ^{40}K in soils. It was noted that the specific activity of ^{40}K was greater than that of ^{232}Th and that of ^{232}Th was greater than that of ^{238}U in the soil samples collected from the four gold mines. Generally, the specific activity of ^{40}K is greater than that of ^{232}Th which is also greater than that of ^{238}U in soils (UNSCEAR, 2000). This could be due to the percentage difference in their abundance in soils.

However, Okame gold mine had the highest value of specific activity of each of the above three radionuclides. This could be due to the uniqueness in the mineral composition of the soils from this mine.

The specific activity of ^{238}U in the mine tailings samples for all the mines at 95% level of confidence ranged between 7.4 Bqkg^{-1} to 13.2 Bqkg^{-1} with an average of 10.3 Bqkg^{-1}. The calculated F–value (F$_{ratio}$= 0.21) was less than the theoretical value of the F-distribution (F$_{3,6}$ = 4.76) implying that the mean values of ^{238}U were not significantly different in the four gold mines. In the case of ^{232}Th the specific activity at 95% level of confidence ranged from 25.1 Bqkg^{-1} to 32.7 Bqkg^{-1} with a mean of 28.9 Bqkg^{-1}. The calculated F–value (F$_{ratio}$ = 1.16) for the data was less than the theoretical value of the F-distribution (F$_{3,\,6}$ = 4.76) implying that the mean values of ^{232}Th were not significantly different in the four gold mines. Specific activity of ^{40}K at 95% level of confidence ranged between 5.7 Bqkg^{-1} to 217.3 Bqkg^{-1} with a mean of 111.5 Bqkg^{-1}. The calculated F–value (F$_{ratio}$ = 3.16) for the data was less than the theoretical value of the F- distribution (F$_{3,\,28}$ = 4.76) implying that the mean values of ^{40}K were not significantly different in the four gold mines. The insignificant difference in the activity concentrations of ^{238}U, ^{232}Th and ^{40}K in the mine tailings samples could be due to equal washing away of minerals containing these radioisotopes during the stage of processing gold. It was generally noted that the specific activity of ^{40}K was greater than that of ^{232}Th and that of ^{232}Th was greater than that of ^{238}U in the four gold mines. This is due to difference in percentage concentration of these radioisotopes in the mines. The specific activities of ^{238}U in the rock samples for all the sites were between 1.7 Bq kg^{-1} to 27.8 Bqkg^{-1} with a mean of 8.9 Bqkg^{-1}. The calculated F–value (F$_{ratio}$ = 6.65) for the data was greater than the theoretical value of the F- distribution (F$_{3,16}$ = 3.23) at α = 0.05 level of significance implying that the mean values of ^{238}U were significantly different in the four gold mines. The activity specific of ^{232}Th in the rock samples from the four mines ranged from 2.3 Bqkg^{-1} to 66.6 Bqkg^{-1} with a mean of 19.8 Bqkg^{-1}. The calculated F–value (F$_{ratio}$= 6.79) for the data was greater than the theoretical value of the F- distribution (F$_{3,\,16}$ = 3.23) implying that the mean values of ^{232}Th were significantly different in the four gold mines. In the case of ^{40}K, the values of specific activities ranged from 2.1 Bqkg^{-1} to 120.1 Bqkg^{-1} with an average of 5.03 Bqkg^{-1}. The calculated F–value (F$_{ratio}$ = 5.03) for the data was greater

than the theoretical value of the F- distribution ($F_{3,16}$ = 3.23) at α = 0.05 level of significance implying that the mean values of ^{40}K were significantly different in the four gold mines. The significant difference in the activity concentrations of these radioisotopes in the above samples could be due to difference in the concentration of radioactive accessory minerals in rocks from different mines which in most cases determine their activity concentrations. The activity concentrations of ^{40}K were greater than that of ^{232}Th which in turn were greater than that of ^{238}U in most of the samples, this could be as a result of difference in percentage abundance of these radioisotopes in the earth's crust. The activity concentrations of ^{238}U, ^{232}Th and ^{40}K in the soil, mine tailings and rock samples from all the three gold mines were below the world wide average values of 35 Bqkg^{-1}, 30 Bqkg^{-1} and 400Bqkg^{-1} for ^{238}U, ^{232}Thand ^{40}K respectively; with exception of Okame soil samples which had values of activity concentrations slightly higher than the worldwide average values. The specific activities in soil and rock samples from Okame were higher than those from other mines. This could be a result of the mine containing more minerals of higher radionuclides concentrations than other mines (Cuney et al. 1987). These radioactive containing minerals including but not limited to feldspar and greensand in most cases contain a lot of ^{40}K. Minerals such as zircon, iron oxides, fluorite, monazite and others play an important role in determining the distribution of uranium and thorium in soils and rocks. Zircon usually contains uranium and thorium concentrations ranging from 0.01 % to 0.19 % and 1 % to 2 % respectively (Cuney et al.1987). The specific activities of the radionuclides were generally high in soil followed by tailings and lastly rocks. The variation in the values of specific activities of the radionuclides in the samples obtained from the different mines had a corresponding effect on the values of radiological parameters of the respective samples.

The absorbed dose rates in the soil samples at 95 % level of confidence ranged between 41.7 nGyh^{-1} to 76.3 nGyh^{-1} with a mean of 59.0 nGyh^{-1} which is close to the world wide average value of 60 nGyh^{-1} (UNSCEAR, 2000). The calculated F–value (F_{ratio} = 3.82) for the data was greater than the theoretical value of the F- distribution ($F_{3,28}$ = 2.96) at α = 0.05 level of significance implying that the mean values of absorbed dose rates in soil samples from the four gold were significantly different. The absorbed dose rates in mine tailings samples at 95 % level of confidence ranged between 13.3 nGh^{-1} to 32.7 nGyh^{-1}

with an average of 23.0 nGy h^{-1}. The calculated F–value (F$_{ratio}$ = 0.98) for the data was less than the theoretical value of the F- distribution (F$_{3,6}$ = 4.76) at α = 0.05 level of significance implying that the mean values of absorbed dose rates in mine tailings samples from the four gold were not significantly different. Absorbed dose rates in rock samples at 95 % level of confidence ranged between 2.3nGyh^{-1} to 58.0 nGyh^{-1} with an average of 17.8 nGyh^{-1}. The calculated F–value (F$_{ratio}$ = 9.0) for the data was greater than the theoretical value of the F- distribution (F$_{3,16}$ = 3.23) at α = 0.05 level of significance implying that the mean values of absorbed dose rates in rock samples from the four gold were significantly different. The absorbed dose rates in the soil, mine tailings and rocks samples were below the world wide average of 60 nGyh^{-1} (UNSCEAR, 2000) with the exception of two sites this is Busia 90 and Okame gold mines with values of 60.4 nGyh^{-1} ± 2.9 nGyh^{-1} and 75.1 nGyh^{-1} ±8.3 nGyh^{-1} respectively which were slightly higher than the world wide average value. This could be due to the uniqueness in the geology and mineral composition of the soils and rocks in those mines. The above results compare with the result of average absorbed dose of 96.52 nGyh^{-1} in Artisanal Gold mine, Kaduna State, Nigeria as determined by Zakari et al. (2013).

The annual effective doses in the soil samples at 95% level of confidence ranged between 0.051 mSvyr^{-1} to 0.093 mSvyr^{-1}with an average of 0.072 mSvyr^{-1}. The calculated F–value (F$_{ratio}$ = 3.79) for the data was greater than the theoretical value of the F-distribution (F$_{3,28}$ = 2.96) at α = 0.05 level of significance implying that the mean values of annual effective doses in soil samples from the four gold were significantly different. The annual effective doses in mine tailings samples at 95% level of confidence ranged between 0.024 mSvyr^{-1} to 0.050 mSvyr^{-1} with an average of 0.037 mSvyr^{-1} which less is than the average annual effective dose equivalent in mine tailings from Mashonga gold mine Southwestern Uganda of 0.37 ± 0.14 mSvy^{-1} (Silver, 2016). The calculated F–value (F$_{ratio}$ = 0.83) for the data was less than the theoretical value of the F- distribution (F$_{3,6}$ = 4.76) at α = 0.05 level of significance implying that the mean values of annual effective doses in mine tailings samples from the four gold were not significantly different. The annual effective doses in rock samples at 95 % confidence level ranged between 0.011 mSvyr^{-1} to 0.047 mSvyr^{-1} with an average of 0.021 mSvyr^{-1}. The calculated F–value

(F_{ratio} = 8.87) for the data was greater than the theoretical value of the F- distribution ($F_{3,16}$ = 3.23) at α = 0.05 level of significance implying that the mean values of annual effective doses in rock samples from the four gold were significantly different. All the values of the annual effective doses from the four sites considered in this study were below the worldwide average value of 0.41 mSvy^{-1} (UNSCEAR, 2000) and also below 20mSvyr^{-1} maximum permissible dose limit set by ICRP for occupational workers.

The internal hazard indices in the soil samples from the four gold mines at 95 % level of confidence ranged from 0.30 to 0.56 with a mean of 0.43. The calculated F–value (F_{ratio} = 3.82) for the data was greater than the theoretical value of the F- distribution ($F_{3,28}$ = 2.96) at α = 0.05 level of significance implying that the mean values of internal hazard indices in soil samples from the four gold were significantly different. The external hazard indices ranged from 0.27 to 0.47 with a mean of 0.37. The calculated F–value (F_{ratio} = 3.08) for the data was greater than the theoretical value of the F- distribution ($F_{3,28}$ = 2.96) at α = 0.05 level of significance implying that the mean values of external hazard indices in soil samples from the four gold were significantly different. The internal hazard indices in mine tailings samples at 95 % level of confidence ranged from 0.15 to 0.27 with a mean of 0.21. The calculated F–value (F_{ratio} = 0.69) for the data was less than the theoretical value of the F- distribution ($F_{3,6}$ = 4.76) at α = 0.05 level of significance implying that the mean values of internal hazard indices in mine tailings samples from the four gold were not significantly different. The external hazard indices at 95% level of confidence ranged from 0.10 to 0.23 with a mean of 0.19. The calculated F–value (F_{ratio} = 0.84) for the data was less than the theoretical value of the F- distribution ($F_{3,6}$ = 2.96) at α = 0.05 level of significance implying that the mean values of external hazard indices in mine tailings samples from the four gold were not significantly different. In rock samples, the internal hazard indices ranged from 0.02 to 0.43 with a mean of 0.14 The calculated F–value (F_{ratio} = 0.11) for the data was greater than the theoretical value of the F- distribution ($F_{3,16}$ = 3.23) at α = 0.05 level of significance implying that the mean values of internal hazard indices in soil samples from the four gold were not significantly different. The external hazard indices ranged from 0.01 to 0.36 with a mean of 0.11. The calculated F–value (F_{ratio} = 3.82) for the data was less than the theoretical value of the F- distribution ($F_{3,16}$ = 3.23) at α = 0.05 level of significance implying that the mean values

of external hazard indices in rock samples from the four gold were not significantly different. The results of both internal and external hazard indices obtained in this study were less than the average values of internal and external hazard indices of 0.9 ± 0.2 and 0.7 ± 0.2 respectively in Perseus gold mine-Ghana soils and rocks respectively as determined by Darko et al. (2016). The hazard indices in soil, tailings and rock samples from all the four gold mines were below unity, a maximum permissible limit set by ICRP. The hazard indices in soils varied significantly among the mine while in tailings and rock samples, insignificant variation was noted at $\alpha = 0.05$. The variation in hazard indices is affected by the concentration of the radionuclides in the samples taken which depends on the mineral composition of the sample.

The Excess Life time Cancer Risks ($\times 10^{-3}$) to the miners from four gold mines were 0.103 ± 0.061, 0.188 ± 0.097, 0.106 ± 0.084, 0.127 ± 0.072 for Agata, Okome, Busia 90 and Greenstone Resource Limited respectively. Okome gold mine had relatively higher value followed by Greenstone, followed by Busia 90 and lastly Agaata. The results of ELCR obtained in this study are lower than the results of ELCR which ranged from 1.527703×10^{-2} to 7.802913×10^{-3} in gold mine tailings in some locations in Jos Plateau State-Nigeria according to Dalvou et al. (2015).

The absorbed dose rate and annual effective dose varied significantly in soil and rock samples as well as the excess lifetime cancer risk among the mines at $\alpha = 0.05$. This could be attributed to differences in the concentration of the radionuclides ^{238}U, ^{232}Th and ^{40}K in the samples which is always determined by the mineral composition of the soils and rocks of the place. In tailings, the absorbed dose rate, annual effective dose and hazard indices showed no significant variation at $\alpha = 0.05$. This could be due to equal washing away of the radionuclides in the samples during the stage of processing gold hence leaving low concentration of these radionuclides in the residue (tailings). Although the hazard indices in the soil, mine tailings and rock samples from all the areas of study were below unity and most of the radiological parameters were below the maximum permissible limits set by ICRP. (1999) and UNSCEAR. (2000) was, it is important that the miners put on protective gear especially nose mask during mining operations. The

health authorities should ensure proper disposal of the mine wastes to reduce the possibility of accumulation of radiotoxic substances in the mines and their neighborhood.

5.2 Conclusions

From the above discussion, the values of activity concentrations of ^{40}K, ^{232}Th and ^{238}U in the soils were greater than that of the tailings and that of the tailings were greater than of the rocks. Okame gold mine had the highest value of specific activity of ^{238}U and ^{232}Th above the worldwide average values of 32 $Bqkg^{-1}$ and 30 $Bqkg^{-1}$ respectively (UNSCEAR, 2000).

The external and internal hazard indices were all less than one in all the samples analyzed meaning that the risk to respiratory diseases such as asthma, cancer and external diseases such as skin cancer, erythema and cataracts is very low.

The absorbed dose rates were low in two gold mines with the exception of Okame and Busia 90 having values higher than the worldwide average of 60 $nGyh^{-1}$ (UNSCEAR, 2000).

The annual effective dose per site was lower than 20mSv/year, the maximum permissible dose limit set by International Commission on Radiological Protection (ICRP, 2007) for occupational workers.

The Excess Lifetime Cancer Risk values were below the ICRP value hence, pointing to the fact that mining activities in the selected goldmines do not pose any significant radiological health hazard to the miners but the miners in Okame and Busia 90 where the absorbed doses were relatively higher than the world wide average should take safety measures such as putting on gas mask during mining operations.

5.3 Recommendations

Further research should be done in the same mines considered in this study during dry and wet seasons to find out whether seasonal variation can have any significant effect on radiation levels in these mines.

Further research should be done to determine the specific activities and radiological hazard levels in soils and rocks in other mines including those that have been considered in this study using different instrument e.g. High purity germanium detector or survey meter to find out whether the results compare with what have been found in this study.

Further research should be done to validate the results at okame gold mine to find out whether the results compare with what have been found in this study.

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APPENDIX A

RAW DATA FOR AGATA GOLD MINE

Data for soil samples

Sample ID	Photo peak	m/±5.0x 10⁻⁵kg	t/±1s	Sum, N	Rate/ Bq	Centroid/ keV	SD/keV	FWHM/ keV	Radionuclide
A1	1			6699	1.12	195.939	10.311	24.231	Th(Pb-212)
	2	0.68625	6000	736	0.12	244.989	8.012	18.828	U(Pb-214)
	3			2778	0.50	298.648	12.568	29.536	U(Pb-214)
	4			4095	0.68	575.727	24.065	56.065	Th(Ti-208)
	5			482	0.08	1267.485	25.741	60.491	K-40
B1	1	0.75355	6000	6190	1.03	196.144	9.487	22.295	Th(Pb-212)
	2			1236	0.21	246.830	9.904	23.275	U(Pb-214)
	3			3658	0.61	297.286	12.996	30.541	U(Pb-214)
	4			3442	0.57	516.318	19.280	45.309	Th(Ti-208)
	5			139	0.02	1257.531	19.889	46.738	K-40
C1	1	0.66835	6000	4748	0.79	197.310	8.967	21.073	Th(Pb-212)
	2			1000	0.17	246.383	8.377	19.685	U(Pb-214)
	3			3641	0.61	296.991	12.302	28.910	U(Pb-214)
	4			2710	0.45	520.783	15.616	26.697	Th(Ti-208)
	5			887	0.15	1260.088	25.522	59.978	K-40
D1	1	0.6891	6000	7064	1.18	195.826	11.217	26.361	Th(Pb-212)
	2			840	0.14	244.249	11.379	26.741	U(Pb-214)
	3			2528	0.42	298.878	12.433	29.217	U(Pb-214)
	4			3456	0.58	521.541	21.809	51.251	Th(Ti-208)
	5			576	0.10	1268.098	24.074	56.575	K-40
E1	1	0.48930	6006	5924	0.99	197.427	9.643	22.661	Th(Pb-212)
	2			280	0.05	245.568	7.607	17.876	U(Pb-214)
	3			2593	0.43	297.429	11.953	28.089	U(Pb-214)
	4			2444	0.41	515.850	18.593	43.694	Th(Ti-208)
	5			12	0.00	1295.112	0.813	1.910	K-40
F1	1	0.47375	6004	6214	1.03	197.249	9.429	22.159	Th(Pb-212)

	2			86	0.01	233.644	7.409	17.412	U(Pb-214)
	3			2253	0.38	297.493	11.514	27.057	U(Pb-214)
	4			4161	0.69	515.493	22.056	51.831	Th(Ti-208)
	5			959	0.16	1262.357	24.293	57.088	K-40
G1	1	0.73780	6000	9220	1.54	194.944	10.537	24.761	Th(Pb-212)
	2			1736	0.29	249,191	9.480	22.278	U(Pb-214)
	3			4245	0.71	296.009	12.624	29.666	U(Pb-214)
	4			3776	0.63	514.621	17.344	40.759	Th(Ti-208)
	5			729	0.12	1268.044	17.501	41.127	K-40
H1	1	0.55070	6003	5956	0.99	198.881	7.801	18.332	Th(Pb-212)
	2			306	0.05	247.108	6.463	15.187	U(Pb-214)
	3			2814	0.47	302.298	12.568	29.536	U(Pb-214)
	4			2096	0.35	518.811	15.341	36.050	Th(Ti-208)
	5			195	0.03	1269.282	17.081	40.140	K-40

Specific activity of radionuclides and radiological parameters in soil samples

Soil samples	Specific activity /Bqkg^{-1}			Hin	Hex	ADR/ nGyh^{-1}	AEDE/ mSvy^{-1}	ELCR
	^{226}Ra	^{232}Th	^{40}K					
A1	14.6	62.6	50.0	0.33	0.29	46.6	0.057	0.160
B1	17.9	48.9	13.1	0.29	0.24	38.4	0.047	0.132
C1	18.9	43.2	94.5	0.29	0.33	38.8	0.048	0.134
D1	13.5	55.4	59.5	0.32	0.26	42.2	0.052	0.146
E1	15.3	57.7	1.7	0.31	0.26	42.0	0.052	0.146
F1	12.5	90.4	144.1	0.45	0.41	66.4	0.081	0.227
G1	22.7	59.4	70.4	0.37	0.31	49.3	0.060	0.168
H1	14.7	46.2	25.2	0.26	0.22	35.7	0.044	0.123
Mean	16.3	58.0	57.3	0.33	0.29	44.9	0.055	0.156
Std. Dev.	3.1	13.8	45.4	0.06	0.06	9.1	0.011	0.033
Std. Err.	1.1	4.9	16.1	0.02	0.02	3.2	0.004	0.012

Data for mine tailings samples

Sample ID	Photo Peak	m/±5.0x10⁻⁵kg	t/±1s	Sum(N)	Rate/Bq	Centroid/keV	SD/keV	FWHM/keV	Radionuclide
T1	1	0.62480	6003	3752	0.63	198.265	13.899	32.664	Th(Pb-212)
	2			1189	0.20	246.083	11.073	26.021	U(Pb-214)
	3			3078	0.51	313.925	6.538	15.365	U(Pb-214)
	4			2120	0.35	577.847	4.643	10.911	Th(Ti-208)
	5			1077	0.18	1253.004	3.412	8.017	K-40
T2	1	0.56585	6090	4505	0.74	196.658	9.471	22.257	Th(Pb-212)
	2			172	0.03	244.444	8.371	19.671	U(Pb-214)
	3			2086	0.34	301.606	10.793	25.364	U(Pb-214)
	4			1625	0.27	517.050	15.686	35.862	Th(Ti-208)
	5			1732	0.28	1270.792	35.180	82.673	K-40
T3	1	0.56035	6001	3757	0.63	193.495	13.124	30.841	Th(Pb-212)
	2			30	0.00	239.149	3.747	8.805	U(Pb-214)
	3			1295	0.22	294.194	13.377	31.437	U(Pb-214)
	4			1184	0.20	511.830	14.554	34.201	Th(Ti-208)
	5			2519	0.42	1265.389	29.394	69.075	K-40

Specific activity of radionuclides and radiological parameters in mine tailings samples

Tailings samples	Specific activity /Bqkg⁻¹			Hin	Hex	ADR/ nGyh⁻¹	AEDE/ mSvy⁻¹	ELCR
	^{226}Ra	^{232}Th	^{40}K					
T1	19.0	36.2	122.7	0.27	0.22	35.8	0.044	0.123
T2	10.1	34.1	214.8	0.23	0.20	34.2	0.042	0.118
T3	6.0	26.6	320.1	0.20	0.19	32.2	0.039	0.109
Mean ±Std. Err.	11.7±3.1	32.3±2.4	219.2±46.5	0.21 ±0.02	0.20± 0.01	34.1±0.9	0.042±0.001	0.117±0.04
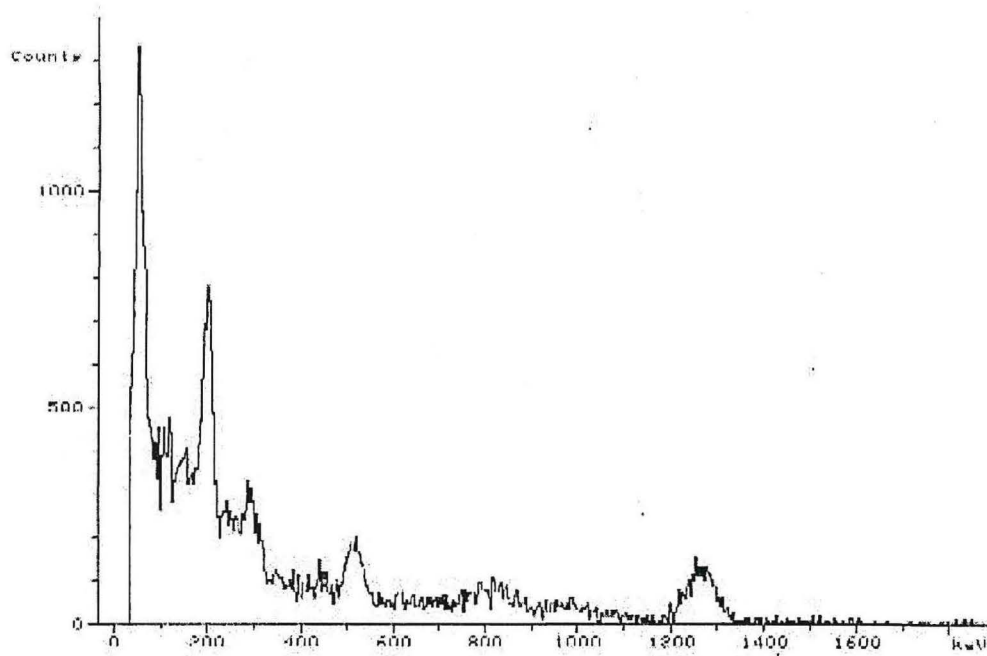
Gamma ray spectrum for Agata mine tailings sample

Data for rock samples

Sample ID	Photo peak	m/±5.0* 10^{-5}kg	t/±1s	Sum, N	Rate/ Bq	Centroid/ keV	SD/keV	FWHM/ keV	Radionuclide
I1	1	0.83890	6003	501	0.08	197.451	17.076	40.129	Th(Pb-212)
	2			145	0.02	281.532	7.632	17.934	U(Pb-214)
	3			223	0.04	306.695	13.019	30.595	U(Pb-214)
	4			30	0.00	524.276	2.799	6.577	Th(Ti-208)
	5			8	0.00	1255.602	1.858	4.367	K-40
J1	1	0.80230	6006	6540	1.09	197.284	10.313	24.235	Th(Pb-212)
	2			870	0.14	245.200	10.190	23.946	U(Pb-214)
	3			2008	0.33	297.997	10.448	24.552	U(Pb-214)
	4			2440	0.41	515.933	18.496	43.466	Th(Ti-208)
	5			1902	0.32	1276.204	39.048	91.762	K-40
K1	1	0.75870	6003	406	0.07	204.108	11.267	26.478	Th(Pb-212)
	2			134	0.02	285.3549	7.084	16.648	U(Pb-214)

	3			159	0.03	318.910	8.209	19.291	U(Pb-214)
	4			14	0.00	518.554	3.128	7.350	Th(Ti-208)
	5			6	0.00	1218.320	1.877	4.412	K-40
L1	1	0.69990	6003	900	0.15	196.265	13.899	32.664	Th(Pb-212)
	2			325	0.05	245.083	11.073	26.021	U(Pb-214)
	3			224	0.04	313.925	6.538	15.365	U(Pb-214)
	4			15	0.00	577.847	4.643	10.911	Th(Ti-208)
	5			38	0.01	1253.004	3.412	8.017	K-40
M1	1	0.84570	6000	555	0.09	197.079	16.635	39.092	Th(Pb-212)
	2			185	0.03	249.771	12.239	28.763	U(Pb-214)
	3			131	0.02	311.265	14.314	33.637	U(Pb-214)
	4			24	0.00	584.356	4.151	9.756	Th(Ti-208)
	5			33	0.01	1233.511	14.937	35.102	K-40

Specific activity of radionuclides and radiological parameters in rock samples

Rock samples	Specific activity /Bqkg^{-1}			Hin	Hex	ADR/ nGyh^{-1}	AEDE/ mSvy^{-1}	ELCR
	^{226}Ra	^{232}Th	^{40}K					
I1	1.3	1.1	0.7	0.01	0.01	1.3	0.007	0.0196
J1	2.6	6.7	2.5	0.04	0.03	5.4	0.041	0.1148
K1	1.1	0.9	0.6	0.01	0.01	1.1	0.001	0.0028
L1	2.4	1.9	3.9	0.02	0.01	2.4	0.003	0.0084
M1	1.2	1.1	2.8	0.01	0.01	1.3	0.002	0.0056
Mean	1.7	2.3	2.1	0.02	0.01	2.3	0.011	0.0360
Std. Dev.	0.6	2.2	1.3	0.01	0.008	1.6	0.015	0.0520
Std. Err.	0.4	1.0	0.6	0.005	0.004	0.7	0.007	0.0230

APPENDIX B

RAW DATA FOR OKAME GOLD MINE

Data for soil samples

Sample ID	Photo peak	m/±5.0x 10⁻⁵kg	t/±1s	Sum,N	Rate/ Bq	Centroid/ keV	SD/keV	FWHM/ keV	Radionuclide
A2	1	0.71150	6248	10743	1.72	193.956	10.759	25.283	Th(Pb-212)
	2			3422	0.55	240.910	9.844	23.132	U(Pb-214)
	3			9054	1.45	296.068	14.854	34.908	U(Pb-214)
	4			6718	1.08	514.799	18.40	44.275	Th(Ti-208)
	5			1174	0.19	1278.613	33.789	79.403	K-40
B2	1	0.70230	6005	12217	2.03	196.237	9.979	23.452	Th(Pb-212)
	2			3143	0.52	247.084	9.185	21.585	U(Pb-214)
	3			8383	1.40	299.470	19.454	45.717	U(Pb-214)
	4			9098	1.52	512.668	20.696	48.635	Th(Ti-208)
	5			3886	0.65	1250.964	26.617	62.551	K-40
C2	1	0.84580	6076	8761	1.44	192.00	10.858	25.517	Th(Pb-212)
	2			2361	0.39	243.332	9.655	22.689	U(Pb-214)
	3			7398	1.22	297.359	12.550	29.493	U(Pb-214)
	4			7794	1.28	516.565	23.400	54.989	Th(Ti-208)
	5			2760	0.05	1252.026	39.029	91.719	K-40
D2	1	0.70230	6005	8359	1.39	195.293	10.253	24.096	Th(Pb-212)
	2			929	0.15	243.460	9.253	21.744	U(Pb-214)
	3			4813	0.80	293.018	13.266	31.176	U(Pb-214)
	4			4799	0.80	515.274	24.203	56.877	Th(Ti-208)
	5			335	0.06	1255.618	11.914	27.997	K-40
E2	1	0.61545	6254	10971	1.75	196.645	10.942		Th(Pb-212)
	2			3520	0.56	245.813	10.937	25.713	U(Pb-214)
	3			6430	1.03	295.312	12.224	25.702	U(Pb-214)
	4			6854	1.10	517.290	22.374	28.726	Th(Ti-208)
	5			3320	0.53	1252.530	30.266	52.579	K-40
								71.125	

F2	1	0.66375	6000	6	1.13	197.490	9.369	22.016	Th(Pb-212)
	2			1196	0.20	243.839	10.141	23.830	U(Pb-214)
	3			3233	0.54	296.348	12.604	29.620	U(Pb-214)
	4			3565	0.59	516.231	18.866	44.335	Th(Ti-208)
	5			742774	0.12	1269.972	16.779	39.430	K-40
G2	1	0.87200	7570	6539	0.86	193.375	10.205	23.983	Th(Pb-212)
	2			2794	0.37	245.466	11.070	26.015	U(Pb-214)
	3			4428	0.58	295.062	13.999	32.897	U(Pb-214)
	4			6582	0.87	514.863	23.893	56.149	Th(Ti-208)
	5			1355	0.18	1249.902	23.315	54.790	K-40
H2	1	0.72165	6000	5450	0.91	196.880	9.517	22.364	Th(Pb-212)
	2			2051	0.34	247.281	11.341	26.651	U(Pb-214)
	3			3741	0.62	300.475	17.052	40.073	U(Pb-214)
	4			5207	0.87	519.076	25.310	59.479	Th(Ti-208)
	5			1490	0.25	1364.460	21.516	50.564	K-40

Specific activity of radionuclides and radiological parameters in soil samples

Soil samples	Specific activity /Bqkg^{-1}			Hin	Hex	ADR/ nGyh^{-1}	AEDE/ mSvy^{-1}	ELCR
	^{226}Ra	^{232}Th	^{40}K					
A2	46.8	94.7	112.9	0.64	0.52	83.5	0.102	0.286
B2	45.6	130.6	373.5	0.82	0.71	115.5	0.141	0.395
C2	31.3	89.1	229.5	0.56	0.58	77.8	0.095	0.266
D2	26.7	89.0	41.6	0.50	0.42	67.8	0.083	0.232
E2	44.4	111.6	368.6	0.74	0.63	103.3	0.127	0.356
F2	18.5	58.3	76.6	0.34	0.29	47.0	0.058	0.162
G2	19.0	57.5	87.7	0.34	0.29	47.2	0.058	0.162
H2	23.0	69.9	147.1	0.42	0.26	59.0	0.072	0.202
Mean	31.9	87.6	179.7	0.55	0.46	75.1	0.092	0.258
Std. Dev.	11.3	23.9	122	0.16	0.16	23.4	0.0290	0.086
Std. Err.	4.0	8.4	43.1	0.06	0.06	8.3	0.010	0.030
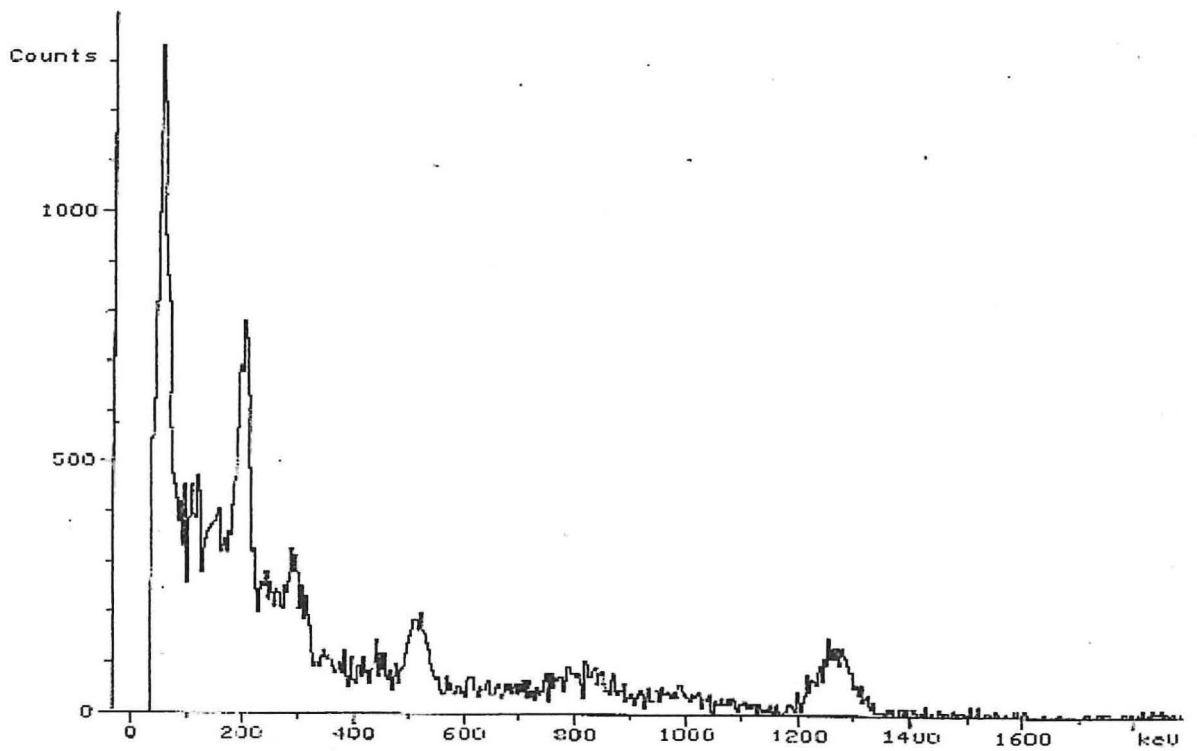
Gamma ray spectrum for a soil sample from Okame gold mine

Data for mines tailings samples

Sample ID	Photo Peak	m/±5.0x10⁻⁵kg	t/±1s	Sum(N)	Rate/Bq	Centroid/keV	SD/keV	FWHM/keV	Radionuclide
T4	1	0.61975	6001	2281	0.56	194.513	11.829	27.798	Th(Pb-212)
	2			556	0.09	244.337	8.618	20.252	U(Pb-214)
	3			1736	0.29	297.336	15.562	36.571	U(Pb-214)
	4			1240	0.21	517.773	17.920	42.112	Th(Ti-208)
	5			107	0.02	1256.870	7.762	18.240	K-40
T5	1	0.63990	6037	3864	0.64	195.173	11.799	27.728	Th(Pb-212)
	2			1079	0.18	248.234	10.288	24.177	U(Pb-214)
	3			1958	0.32	297.446	12.603	29.617	U(Pb-214)

				1670	0.28	517.543	18.852	44.303	Th(Ti-208)
	4			422	0.07	1268.000	27.556	27.556	K-40
	5								
T	1	0.78110	6000	3101	0.52	196.265	12.671	29.778	Th(Pb-212)
	2			520	0.09	247.032	8.835	20.057	U(Pb-214)
	3			1949	0.32	293.686	16.313	38.336	U(Pb-214)
	4			1938	0.32	514.129	24.836	58.365	Th(Ti-208)
	5			580	0.10	1257.035	24.247	56.979	K-40

Specific activity of radionuclides and radiological parameters in mine tailings samples

Tailings samples	Specific activity /Bqkg^{-1}			Hin	Hex	ADR/ nGyh^{-1}	AEDE/ mSvy^{-1}	ELCR
	^{226}Ra	^{232}Th	^{40}K					
T4	10.2	24.0	12.3	0.15	0.12	19.7	0.024	0.067
T5	13.5	29.6	46.7	0.20	0.18	26.1	0.032	0.090
T6	8.6	25.9	52.9	0.16	0.13	21.8	0.027	0.076
Mean ± Std. Err.	10.8±1.2	26.5±1.3	37.3±10.3	0.17±0.01	0.14±0.02	22.5±1.5	0.028±0.002	0.078±0.007

Data for rock samples

Sample ID	Photo peak	m/±0.00 005kg	t/±1s	Sum (N)	Rate(R)	Centroid/ keV	SD/keV	FWHM/ keV	Radionuclide
I4	1	0.83430	6015	17269	2.87	197.080	10.886	25.581	Th(Pb-212)
	2			5672	0.94	245.289	11.546	27.134	U(Pb-214)
	3			10628	1.77	297.442	12.122	28.486	U(Pb-214)
	4			12767	2.12	514.668	22.895	53.804	Th(Ti-208)
	5			167	0.03	1293.217	31.469	74.000	K-40
J4	1	0.89240	6600	1341	0.20	191.800	12.083	28.395	Th(Pb-212)
	2			320	0.05	241.089	11.747	27.606	U(Pb-214)
	3			583	0.09	299.532	13.485	31.690	U(Pb-214)
	4			579	0.09	511.208	17.284	40.618	Th(Ti-208)
	5			34	0.01	1212.025	25.863	60.778	K-40
K4	1	0.83525	6357	10000	1.57	196.323	11.041	25.947	Th(Pb-212)

	No.								
	2			2825	0.44	244.411	9.946	23.374	U(Pb-214)
	3			6141	0.97	296.160	11.053	25.975	U(Pb-214)
	4			5193	0.82	516.872	17.675	41.537	Th(Ti-208)
	5			3160	0.50	1250.220	36.510	85.79	K-40
L4	1	0.92350	6248	790	0.13	196.113	14.145	33.240	Th(Pb-212)
	2			220	0.04	238.739	5.477	12.871	U(Pb-214)
	3			769	0.12	290.913	18.384	43.201	U(Pb-214)
	4			212	0.03	507.913	17.157	40.319	Th(Ti-208)
	5			990	0.02	1237.228	15.286	35.922	K-40
M4	1	0.86610	6000	6053	1.01	196.353	9.148	21.498	Th(Pb-212)
	2			1004	0.17	243.823	7.537	17.713	U((Pb-214)
	3			4517	0.75	297.301	11.401	26.792	U(Pb-214)
	4			4514	0.75	515.928	19.635	46.143	Th(Ti-208)
	5			66	0.01	1256.412	6.415	15.076	K-40

Specific activity of radionuclides and radiological parameters in rock samples

Rock samples	Specific Activity /Bqkg^{-1}			Hin	Hex	ADR/ nGyh^{-1}	AEDE/ mSvy^{-1}	ELCR
	^{226}Ra	^{232}Th	^{40}K					
I4	55.6	154.2	14.2	0.90	0.75	119.4	0.146	0.4088
J4	10.1	36.2	168.7	0.23	0.20	33.6	0.041	0.1148
K4	28.6	63.9	254.3	0.45	0.38	62.4	0.077	0.2156
L4	41.6	63.0	69.0	0.48	0.37	60.1	0.074	0.2072
M4	3.0	15.6	94.4	0.10	0.09	14.7	0.071	0.1988
Mean	27.8	66.6	120.1	0.43	0.36	58.0	0.047	0.2290
Std. Dev.	19.5	47.4	83.5	0.27	0.22	35.4	0.043	0.1080
Std. Err.	8.7	21.2	37.3	0.12	0.10	15.8	0.019	0.0480
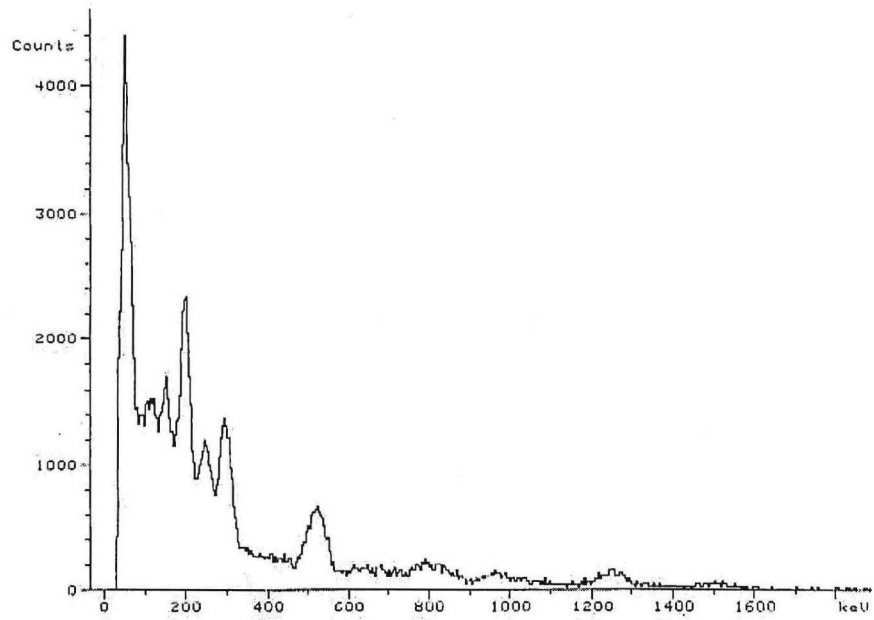
Gamma ray spectrum for a rock sample from Okame gold mine

APPENDIX C

RAW DATA FOR BUSIA 90 GOLD MINE

Data for soil samples

Sample ID	Photo peak	m/±5.0*10⁻⁵kg	t/±1s	Sum,N	Rate/ Bq	Centroid/ keV	SD/keV	FWHM/ keV	Radionuclide
A3	1	0.63735	6000	6576	1.10	195.833	11.208	26.338	Th(Pb-212)
	2			919	0.15	239.578	9.186	21.588	U(Pb-214)
	3			1923	0.32	294.047	11.587	27.230	U(Pb-214)
	4			4196	0.70	514.912	23.344	54.859	Th(Ti-208)
	5			2073	0.35	1266.59	27.027	63.518	K-40
B3	1	0.57505	6000	6370	1.06	196.644	8.439	19.831	Th(Pb-212)
	2			922	0.15	245.099	9.212	21.649	U(Pb-214)
	3			2433	0.41	297.921	10.408	24.459	U(Pb-214)
	4			4490	0.75	515.628	24.371	57.271	Th(Ti-208)
	5					344.827	9.203	21.628	K-40
C3	1	0.56105	6008	9687	1.61	197.480	11.347	26.666	Th(Pb-212)
	2			614	0.10	249.195	7.044	16.552	U(Pb-214)
	3			3539	0.59	297.422	11.870	27.896	U(Pb-214)
	4			4568	0.76	517.523	20.048	47.114	Th(Ti-208)
	5			24	0.00	1261.321	11.207	26.337	K-40
D3	1	0.61390	6001	8725	1.45	196.348	9.778	22.978	Th(Pb-212)
	2			1699	0.28	244.110	10.325	24.264	U(Pb-214)
	3			4109	0.68	296.094	12.743	29.946	U(Pb-214)
	4			3445	0.57	514.773	17.080	40.139	Th(Ti-208)
	5			109	0.02	1265.273	8.843	20.781	K-40
E3	1	0.46065	6000	5984	1.00	194.545	9.371	22.021	Th(Pb-212)
	2			1356	0.23	244.376	10.477	24.621	U(Pb-214)
	3			2853	0.48	295.022	11.602	27.264	U(Pb-214)
	4			3851	0.64	515.781	20.318	47.748	Th(Ti-208)
	5			21	0.00	1261.979	8.62-0	20.256	K-40
F3	1	0.70710	6000	7140	1.19	196.553	9.514	22.358	Th(Pb-212)

	2			1296	0.22	245.826	8.190	19.247	U(Pb-214)
	3			4457	0.74	297.180	10.359	24.343	U(Pb-214)
	4			4596	0.77	519.571	18.289	42.979	Th(Ti-208)
	5			620	0.10	1243.164	30.790	72.356	K-40
G3	1	0.64475	6035	6888	1.14	196.348	9.739	22.887	Th(Pb-212)
	2			1035	0.17	243.705	9.494	22.310	U(Pb-214)
	3			3600	0.60	297.271	12.237	28.758	U(Pb-214)
	4			3781	0.63	516.774	19.836	46.614	Th(Ti-208)
	5			517	0.09	1244.587	32.803	77.087	K-40
H3	1	0.69665	6000	7244	1.21	197.202	9.489	22.298	Th(Pb-212)
	2			1304	0.22	244.841	8.825	20.738	U(Pb-214)
	3			4410	0.74	298.643	12.028	28.266	U(Pb-214)
	4			6105	1.02	518.783	23.407	55.005	Th(Ti-208)
	5			2985	0.50	1267.459	30.447	71.551	K-40

Specific activity of radionuclides and radiological parameters in soil samples

Soil samples	Specific activity /Bqkg^{-1}			Hin	Hex	ADR/ nGyh^{-1}	AEDE/ mSvy^{-1}	ELCR
	^{226}Ra	^{232}Th	^{40}K					
A3	12.6	68.5	231.7	0.38	0.35	56.9	0.070	0.196
B3	16.2	79.6	274.7	0.45	0.41	67.0	0.082	0.230
C3	19.6	90.7	3.0	0.46	0.40	64.0	0.078	0.218
D3	26.5	65.8	12.6	0.40	0.33	52.5	0.064	0.179
E3	25.8	86.8	3.2	0.47	0.41	64.5	0.079	0.221
F3	22.2	67.5	62.5	0.39	0.33	53.6	0.066	0.185
G3	19.5	62.7	56.8	0.36	0.31	49.2	0.060	0.168
H3	22.4	86.6	305.2	0.52	0.46	75.4	0.092	0.258
Mean	20.6	76.0	118.7	0.43	0.38	60.4	0.074	0.207
Std. Dev.	4.4	10.4	120.9	0.05	0.05	8.3	0.010	0.030
Std. Err.	1.6	3.7	42.7	0.02	0.02	2.9	0.004	0.011

Data for tailings samples

Sample ID	Photo Peak	m/±5.0x10⁻⁵kg	t/±1s	Sum(N)	Rate/ Bq	Centroid/ keV	SD/keV	FWHM/keV	Radionuclide
T7	1	0.74525	6113	6331	1.04	196.430	10.757	5.279	Th(Pb-212)
	2			1534	0.25	242.071	9.295	21.843	U(Pb-214)
	3			4242	0.69	296.966	14.276	33.548	U(Pb-214)
	4			4172	0.68	511.272	20.819	48.924	Th(Ti-208)
	5			1919	0.31	1247.455	38.316	90.043	K-40
T8	1	0.89030	6601	1662	0.25	192.761	14.058	33.036	Th(Pb-212)
	2			211	0.03	240.559	7.574	17.799	U(Pb-214)
	3			848	0.13	295.956	15.940	37.459	U(Pb-214)
	4			701	0.11	512.270	19.203	45.126	Th(Ti-208)
	5			244	0.04	1227.123	29.396	69.081	K-40

Specific activity of radionuclides and radiological parameters in tailings samples

Tailings samples	Specific activity /Bqkg⁻¹			Hin	Hex	ADR/ nGyh⁻¹	AEDE/ mSvy⁻¹	ELCR
	^{226}Ra	^{232}Th	^{40}K					
T7	21.1	45.3	180.0	0.33	0.27	44.6	0.055	0.154
T8	2.9	8.2	17±.7	0.05	0.04	7.0	0.009	0.025
Mean± Std. Err	12.0±6.4	26.8±13.4	62.8±48.8	0.19±0.10	0.16±0.08	25.8±13.3	0.032±0.016	0.090±0.065
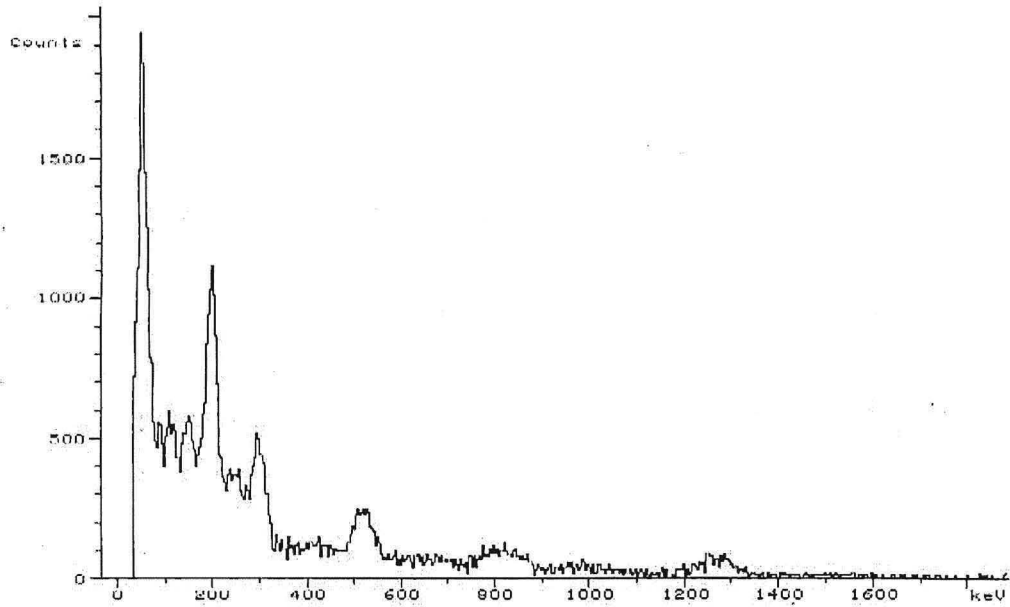
Gamma ray spectrum for Busia 90 gold mine tailings sample

Data for rock samples

Sample ID	Photo peak	m/±5.0x 10^{-5}kg	t/±1s	Sum (N)	Rate/ Bq	Centroid/ keV	SD/keV	FWHM/k eV	Radionuclide
I3	1	0.80990	6002	879	0.15	210.187	15.574	36.600	Th(Pb-212)
	2			494	0.08	298.337	15.810	37.154	U(Pb-214)
	3			192	0.03	349.291	10.370	24.370	U(Pb-214)
	4			20	0.00	526.467	7.308	17.173	Th(Ti-208)
	5			325	0.05	1261.341	21.809	51.251	K-40
J3	1	0.66810	6002	1085	0.18	193.206	14.240	33.465	Th(Pb-212)
	2			335	0.06	251.773	14.354	33.731	U(Pb-214)
	3			566	0.09	308.237	15.062	35.396	U(Pb-214)
	4			92	0.02	522.589	4.210	9.894	Th(Ti-208)
	5			952	0.16	1266.803	22.825	53.639	K-40
K3	1	0.82330	6001	1976	0.33	194.237	13.014	30.584	Th(Pb-212)
	2			230	0.04	247.986	10.173	23.907	U(Pb-214)
	3			669	0.11	296.643	14.305	33.616	U(Pb-214)
	4			1228	0.20	516.278	19.336	45.440	Th(Ti-208)

	5			1091	0.18	1262.989	29.121	68.435	K-40
L3	1	0.82480	6001	2901	0.48	197.300	11.899	27.962	Th(Pb-212)
	2			669	0.11	247.834	14.188	33.343	U(Pb-214)
	3			1136	0.19	303.151	17.754	41.721	U(Pb-214)
	4			1429	0.24	516.951	20.956	42.247	Th(Ti-208)
	5			528	0.09	1258.971	19.872	46.699	K-40
M3	1	0.66430	6003	1186	0.20	195.679	15.653	36.784	Th(Pb-212)
	2			437	0.07	245.409	11.617	27.302	U(Pb-214)
	3			305	0.05	307.641	10.938	25.703	U(Pb-214)
	4			106	0.02	520.639	7.442	17.488	Th(Ti-208)
	5			30	0.00	1253.241	3.127	7.348	K-40

Specific activity of radionuclides and radiological parameters in rock samples

Rock samples	Specific Activity /Bqkg^{-1}			Hin	Hex	ADR/ nGyh^{-1}	AEDE/ mSvy^{-1}	ELCR
	^{226}Ra	^{232}Th	^{40}K					
I3	2.7	1.7	28.6	0.03	0.02	3.5	0.004	0.0112
J3	2.1	3.4	101.5	0.05	0.04	7.3	0.009	0.0252
K3	1.4	1.9	5.3	0.02	0.01	14.7	0.002	0.0056
L3	6.3	19.1	45.6	0.12	0.10	2.0	0.020	0.0560
M3	3.5	3.8	3.2	0.03	0.02	4.0	0.005	0.0140
Mean	3.2	6.0	36.8	0.05	0.04	6.3	0.008	0.0220
Std. Dev.	1.7	6.6	35.9	0.04	0.03	4.5	0.006	0.0200
Std. Err.	0.8	3.0	16.127	0.02	0.01	2.0	0.003	0.0090

APPENDIX D

RAW DATA FOR GREENSTONE RESOURCE LIMITED GOLD MINE

Data for soil samples

Sample ID	Photo peak	m/±5.0*10⁻⁵kg	t/±1s	Sum,N	Rate/ Bq	Centroid/ keV	SD/keV	FWHM/ keV	Radionuclide
A4	1	0.78950	6001	3642	0.61	197.054	11.203	26.326	Th(Pb-212)
	2			523	0.09	244.788	11.326	26.616	U(Pb-214)
	3			1181	0.20	294.502	12.615	29.646	U(Pb-214)
	4			1184	0.20	511.830	14.554	34.201	Th(Ti-208)
	5			2080	0.35	1263.358	27.469	64.553	K-40
B4	1	0.63295	6012	10983	1.83	196.263	9.728	22.861	Th(Pb-212)
	2			1844	0.31	245.516	7.576	17.803	U(Pb-214)
	3			5389	0.90	297.638	10.177	23.916	U(Pb-214)
	4			5196	0.86	518.691	16.680	39.199	Th(Ti-208)
	5			373	0.06	1262.410	15.007	35.265	K-40
C4	1	0.73125	6000	6012	1.00	198.607	8.953	21.038	Th(Pb-212)
	2			1239	0.21	247.351	10.101	23,737	U(Pb-214)
	3			41342	0.69	300.919	17.219	40.464	U(Pb-214)
	4			985	0.50	516.637	19.365	45.507	Th(Ti-208)
	5			4469	0.74	1262.218	44.790	105.256	K-40
D4	1	0.7143	6355	11354	1.79	193.885	9.695	22.783	Th(Pb-212)
	2			4121	0.65	245.791	12.351	29.025	U(Pb-214)
	3			8231	1.30	295.557	12.174	28.608	U(Pb-214)
	4			6402	1.01	517.390	16.517	38.815	Th(Ti-208)
	5			5589	0.88	1260.693	50.725	119.203	K-40
E4	1	0.64700	6244	10153	1.63	195.492	11.609	27.279	Th(Pb-212)
	2			2771	0.44	243.031	9.836	23.115	U(Pb-214)
	3			5432	0.87	294.092	14.213	33.400	U(Pb-214)
	4			4014	0.64	513.133	17.253	40.543	Th(Ti-208)
	5			420	0.07	1254.094	11.541	27.121	K-40
F4	1	0.47995	6039	5468	0.91	195.994	8.997	21.143	Th(Pb-212)

	2			1877	0.31	246.887	12.246	28.777	U(Pb-214)
	3			1838	0.30	298.147	10.374	24.379	U(Pb-214)
	4			1466	0.24	520.839	17.009	39.972	Th(Ti-208)
	5			1089	0.18	1270.154	37.588	88.332	K-40
G4	1	0.47550	6000	4749	0.79	195.879	9.587	22.529	Th(Pb-212)
	2			385	0.06	240.472	8.861	20.824	U(Pb-214)
	3			2307	0.38	299.457	14.605	14.605	U(Pb-214)
	4			2374	0.40	513.425	20.841	48.976	Th(Ti-208)
	5			19	0.00	1292.060	9.026	21.212	K-40
H4	1	0.66830	6003	8557	1.42	197.103	9.895	23.252	Th(Pb-212)
	2			966	0.16	243.648	7.650	17.978	U(Pb-214)
	3			3518	0.59	295.526	10.785	25.344	U(Pb-214)
	4			5022	0.84	516.479	21.831	51.303	Th(Ti-208)
	5			310	0.05	1262,374	9.947	23.375	K-40

Specific activity of radionuclides and radiological parameters in soil samples

Soil samples	Specific activity /Bqkg^{-1}			Hin	Hex	ADR/ nGyh^{-1}	AEDE/ mSvy^{-1}	ELCR
	^{226}Ra	^{232}Th	^{40}K					
A4	6.1	18.7	187.6	0.14	0.13	21.9	0.027	0.076
B4	31.5	91.3	41.9	0.53	0.45	71.4	0.088	0.246
C4	20.1	44.9	435.3	0.37	0.32	54.6	0.067	0.188
D4	46.4	90.4	526.2	0.71	0.58	98.0	0.120	0.336
E4	34.7	69.9	44.4	0.47	0.37	60.1	0.074	0.207
F4	23.2	40.6	160.6	0.32	0.25	41.9	0.051	0.143
G4	15.0	54.9	2.0	0.29	0.25	40.2	0.049	0.137
H4	18.2	79.5	3.3	0.41	0.36	56.6	0.069	0.193
Mean	24.4	61.3	175.1	0.41	0.34	55.6	0.068	0.191
Std. Dev.	11.8	24.3	189.0	0.16	0.13	21.3	0.026	0.078
Std. Err.	4.2	8.6	66.8	0.06	0.05	7.5	0.009	0.028

Data for mines tailings samples

Sample ID	Photo Peak	m/±5.0x10⁻⁵kg	t/±1s	Sum(N)	Rate/Bq	Centroid/keV	SD/keV	FWHM/keV	Radionuclide
T9	1	0.68410	6000	3642	0.61	194.570	10.395	24.429	Th(Pb-212)
	2			793	0.13	253.793	11.194	26.306	U(Pb-214)
	3			1938	0.32	297.840	13.260	31.162	U(Pb-214)
	4			2651	0.44	515.382	22.525	52.934	Th(Ti-208)
	5			524	0.09	1266.210	31.123	73.138	K-40
T10	1	0.70845	6003	6200	1.03	196.008	9.895	23.253	Th(Pb-212)
	2			926	0.15	245.450	9.049	21.266	U(Pb-214)
	3			2857	0.48	296.365	10.711	25.170	U(Pb-214)
	4			3290	0.55	519.415	19.047	44.761	Th(Ti-208)
	5			1259	0.21	1261.249	35.177	82.609	K-40

Specific activity of radionuclides and radiological parameters in mine tailings samples

Tailings samples	Specific activity/Bqkg⁻¹			Hin	Hex	ADR/nGyh⁻¹	AEDE/mSvy⁻¹	ELCR
	^{226}Ra	^{232}Th	^{40}K					
T9	16.2	39.3	54.6	0.25	0.21	33.5	0.041	0.115
T10	14.7	50.3	126.5	0.30	0.26	42.4	0.052	0.146
Mean± Std. Err.	15.5±0.6	44.8±3.9	90.6±25.4	0.28±0.02	0.24±0.02	38.0±3.1	0.047±0.004	0.131±0.016

Data for rock samples

Sample ID	Photo peak	m/±5.0*10⁻⁵kg	t/±1s	Sum (N)	Rate/Bq	Centroid/keV	SD/keV	FWHM/keV	Radionuclide
I2	1	0.88625	6001	7824	1.30	195.279	9.139	21.477	Th(Pb-212)
	2			4929	0.82	247.822	11.263	26.468	U(Pb-214)
	3			7814	1.30	297.729	12.189	28.645	U(Pb-214)
	4			5467	0.98	522.090	16.543	38.876	Th(Ti-208)
	5			859	0.14	1274.879	28.749	67.559	K-40
J2	1	0.89125	6002	1640	0.27	197.422	15.671	36.828	Th(Pb-212)
	2			488	0.08	265.350	17.131	40.258	U(Pb-214)
	3			405	0.07	307.953	11.441	26.886	U(Pb-214)
	4			390	0.06	515.986	14.830	34.849	Th(Ti-208)
	5			224	0.04	1247.036	18.317	43.043	K-40
K2	1	0.87975	6344	1740	0.27	193.144	13.528	31.790	Th(Pb-212)
	2			152	0.02	242.966	4.644	10.914	U(Pb-214)
	3			1378	0.22	277.713	25.635	60.242	U(Pb-214)
	4			555	0.09	516.374	17.950	42.183	Th(Ti-208)
	5			209	0.03	1250.830	20.172	47.405	K-40
L2	1	0.91930	6024	761	0.13	195.796	15.155	35.614	Th(Pb-212)
	2			377	0.06	246.494	10.783	25.339	U(Pb-214)
	3			489	0.08	295.829	16.062	37.746	U(Pb-214)
	4			199	0.03	505.602	17.496	4.115	Th(Ti-208)
	5			736	0.02	1229.254	26.663	62.657	K-40
M2	1	0.92760	6725	1025	0.15	199.031	17.276	40.598	Th(Pb-212)
	2			219	0.03	238.315	4.670	10.974	U(Pb-214)
	3			254	0.04	283.978	12.282	28.862	U(Pb-214)
	4			75	0.01	517.717	6.654	15.637	Th(Ti-208)
	5			57	0.01	1261.173	12.686	29.811	K-40

Specific activity of radionuclides and radiological parameters in rock samples

Rock samples	Specific Activity /Bqkg^{-1}			Hin	Hex	ADR/ nGyh^{-1}	AEDE/ mSvy^{-1}	ELCR
	^{226}Ra	^{232}Th	^{40}K					
I2	2.8	2.9	7.3	0.03	0.02	2.6	0.074	0.2072
J2	3.1	6.1	17.9	0.04	0.04	5.9	0.003	0.0084
K2	4.3	7.5	16.0	0.06	0.04	7.2	0.009	0.0252
L2	2.8	2.9	56.8	0.04	0.03	5.4	0.007	0.0196
M2	1.4	1.9	3.9	0.02	0.01	2.0	0.002	0.0056
Mean	2.9	4.3	20.4	0.04	0.03	4.6	0.019	0.0530
Std. Dev.	0.9	2.2	18.9	0.01	0.01	2.0	0.028	0.0860
Std. Err.	0.4	1.0	8.5	0.006	0.006	0.9	0.013	0.0390

Correction coefficient of sodium iodide scintillation detector for different radionuclides

Energy/keV	Radionuclides	Correction coefficient, C
238	Th(Pb-212)	0.0608
295	U(Pb-214)	0.0237
352	U(Pb-214)	0.0333
580	Th(Tl-208)	0.0101
1460	K-40	2.34×10^{-3}